HyDelta

WP1B – Gas stations

D1B.4 – Dust transport with hydrogen and natural gas and its effect on gas filters (Part 1)

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Document summary

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Executive summary

Given the current importance of energy transition, there is an ongoing interest in assessing whether the existing natural gas infrastructure can be used to transport hydrogen. Research conducted as part of the HyDelta 1B work package focused on identifying if existing gas pressure reducing stations are - or could be made - suitable for this purpose. One point considered in this respect was the filters used in gas pressure reducing stations. They filter incoming gas to remove dust and protect active components in the station and the downstream network.

Past research by Kiwa has shown that the gas transport velocity [1] has to be a factor of 3 higher when transporting hydrogen if the same amount of energy is to be transported. It is currently unknown how this increase in flow rate will affect gas filters. Therefore, the objective of this research is to answer the following main research question:

> **Will it be possible to continue to use the current type of filter element - without any modifications - to safely and efficiently filter dust present in the natural gas network when the transition is made to hydrogen?**

The answer to this main research question will be multi-faceted and impossible to arrive at unequivocally without first gaining an understanding of the basic physics of dust particles in a hydrogen environment. The sub-questions below have been drafted with a view to gaining this understanding and, by doing this, answer the main research question. Sub-questions 1 to 4 will be answered in this report; Questions 5 and 6 will be addressed in follow-up research:

1. *How will the transition from natural gas to hydrogen and the increase in gas velocity affect dust transport?*
2. *Will the increase in gas velocity lead to an increase in dust in the filters?*
3. *Which characteristics of dust in the natural gas network are important to take into account when implementing a test programme?*
4. *Which variables need to be studied in a test programme to assess the risk as regards the ability to transport dust after making the transition from natural gas to hydrogen?*
5. *How will operational gas network pressure affect dust transport?*
6. *Which consequences will there be for filters where dust transport is concerned?*

The object of the sub-questions above is to provide an insight into the transport of dust in natural gas and hydrogen. It will be possible to answer the main research question via the sub-questions if two assumptions are made. Firstly, the change in medium from natural gas to hydrogen will have little to no effect on the filtration properties of the filter. Secondly, the impact a dust particle has on a filter will be negligible given the mass and strength of the filter. These assumptions simplify the main research question and mean that it can be answered via just some of the sub-questions above.

Efforts to answer the sub-questions above started with a literature review. Although this yielded several theories, none included research on dust transport phenomena with hydrogen. Experiments were then carried out to ascertain which of these theories reflects reality. The literature review was then used as the basis for the pragmatic development of a test apparatus. Armed with this transparent apparatus, tests were carried out in six steps. The first set of tests tested reproducibility, time dependence and mass dependence. The results of these tests will support the selections made when performing the second set of tests.

For example, terminal velocity (which is defined as the tipping point at which a dust particle starts to move with the gas) in relation to the dust particle size was researched for air, natural gas and hydrogen. The experiments carried out have led to the conclusion that the terminal velocity is between 1.2 and 2.6 times higher for hydrogen than the terminal velocity for natural gas. When combined with the knowledge that hydrogen needs velocity to be increased by a factor of 3, it can be concluded that it is probable that more dust will be transported initially if the network transitions to the distribution of hydrogen. This is the most important conclusion to emerge from these tests. However, the biggest qualification of this conclusion is that dust transport depends on both the mean dust-particle size and the density of the dust.

The research conducted would seem to show a possible relationship between the momentum (rho-v^2) of the gas and the amount of dust transported. It is recommended that this momentum theory be the subject of further theoretical and experimental research. If understood, this relationship could be an enabler to understanding dust transport phenomena in other gases and dust transport with gases at different pressures. It is also recommended that tests are carried out using actual stations, pressures and flows to ensure the validation of the models and assumptions.

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1. Introduction

As part of the HyDelta national research programme, researchers in the ‘gas stations’ work package considered the research question relating to the suitability of grid the current gas network for the distribution of hydrogen. One sub-question is the extent to which current gas stations are suitable for hydrogen. Stations are fitted with filters to avoid dust ending up in vulnerable components. As another medium will be transported through the gas station and filter with the hydrogen, this gives rise to the question of the extent to which gas filters will be affected when hydrogen flows through them. Will the transition to hydrogen affect the extent to which filters are contaminated with dust (from the gas network) and, if yes, should the maintenance regime be modified?

The objective of the current research is to answer the following main research question:

> **Will it be possible to continue to use the current type of dust filter - without any modifications - to safely and efficiently filter dust present in the gas distribution network when the transition is made to hydrogen?**

Dutch regional system operators want to establish the effect on the transport of dust in existing - or slightly modified - gas pressure regulating stations for natural gas and pure hydrogen (H_2). Dust is present in the distribution network due to the ageing of networks and work done on networks in the past.

Explanation:
Hydrogen has different physical properties to natural gas and the gas velocity of hydrogen will need to be approximately a factor of 3 higher to supply the same amount of energy as natural gas. This is illustrated on the basis of energy density and calorific value in the figure on the right.

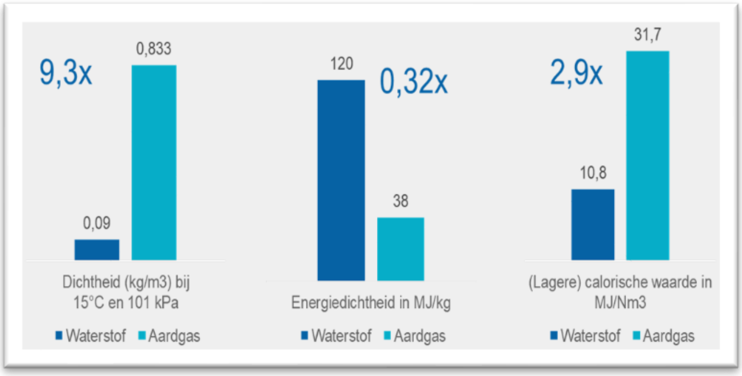

Figure 1: properties of natural gas and hydrogen

Objective

To be able to answer the problem definition above, consideration must first be given to the physical mechanisms that underlie the contamination of filters. This is because the most important cause of contamination is the dust transported before it reaches the filter. However, little is currently known about dust transport in hydrogen. Hence why the main objective of this research is to gain an insight into the transport of dust in pipelines via practical tests in which air, natural gas and hydrogen are studied as transporting mediums. The tests with air were done because they ca be carried out safely, at less expense and with a lower environmental impact than natural gas and hydrogen. The research has been designed to demonstrate whether or not the amount of dust transported could lead to changes to the maintenance regime for gas filters after the transition from natural gas to hydrogen in the gas distribution network.

Approach

Before carrying out tests with dust, it is necessary to know how dust acts in a gas flow. Basically, three steps were proposed via which this behaviour could be studied and an apparatus was developed on the basis of the variables that influence dust transport. A literature review was carried out in respect of the apparatus, to ensure it was built properly and also to further substantiate the choices made. This review has also made it possible to gain a better understanding of theory on the subject of dust transport.

The test apparatus was used to define the variables better.

Step 1; Use transparent test apparatus to gain understanding and visualise (atmospheric conditions);
Step 2; Carry out tests with natural gas under high pressure (8 bar);
Step 3; Carry out tests with hydrogen under high pressure (8 bar).

The apparatus in Step 1 works under atmospheric pressure, while gas filters in gas stations and the upstream pipeline system of regional network operators are usually operated at about 8 bar. However, Step 1 is necessary to gain appropriate insights into important variables and the influence they have. Added to this, a transparent test apparatus facilitates a visualisation of dust transport and also, very specifically, the conditions in which dust transport takes place (also see Appendix VI). It would be very expensive to gain these insights at a higher pressure level because the complexity of the transparent test apparatus (which is able to withstand high pressure levels) and risks (and, as such, costs too) increase exponentially when the pressure increases.

One complicating factor for the research was how to achieve the controlled dosing of dust into a pipeline, whether or not under pressure and also whether or not filled with a flammable gas. It proved very difficult to find a suitable system that facilitated the above. It was also found that by Step 1 yielded better insights into dust transport that were vital for Steps 2 and 3 on various fronts. To stay on budget and time, this report will focus specifically on Step 1. The research results for this step will be related to the research objective, after which attention will turn to possible follow-up research.

2. Gas pressure regulating station

2.1 Construction of the gas pressure regulating station

In a gas pressure regulating station, the nominal inlet pressure is generally reduced from 8 bar(g) to 100 mbar(g) so that gas can be transported to households in a low pressure network.

A modern gas pressure regulating station is often housed in a stainless steel casing containing the following at the very least:

- An inlet valve that also serves as a safety valve (VA);
- A dust filter;
- A pressure regulator with a safety device mounted on it (safety shut-off valve);
- An exhaust valve: butterfly valve or ball valve type.

Figure 2 shows an open gas pressure regulating station. The gas filter housing is identified in red in the photograph and shown in diagram form to the right of the photograph.

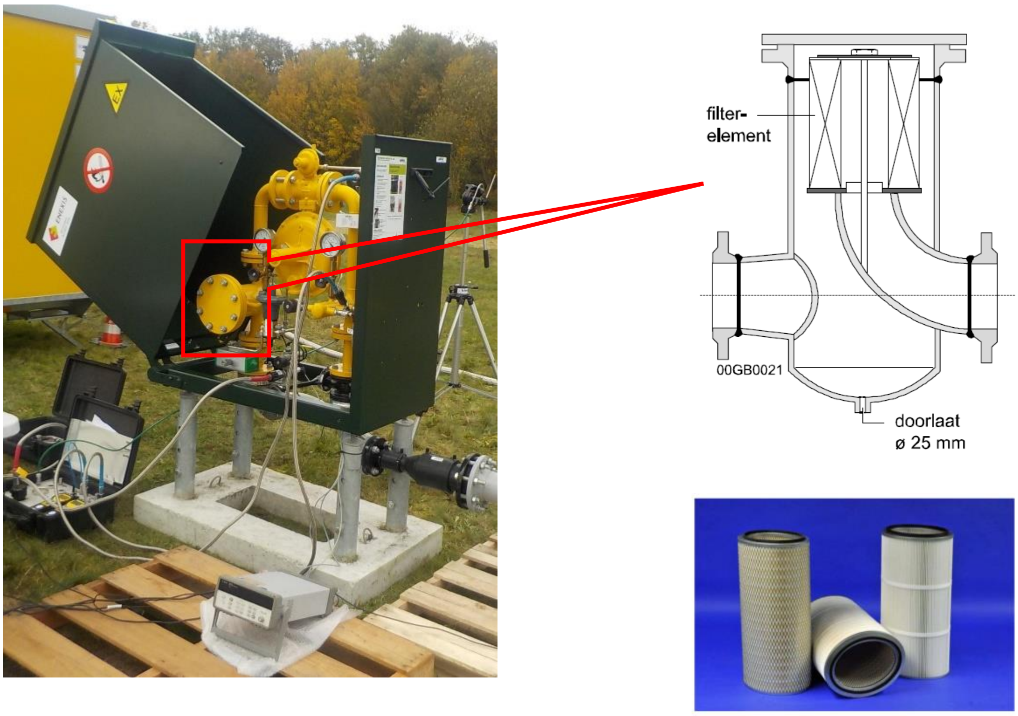

Figure 2: Left - an open gas pressure regulating station (district station). Top right - a gas filter housing. Bottom right - a number of the G-class filters typically used.

2.2 Gas filters

A gas pressure regulating station contains a filter housing with a gas filter in it. The filter stops contaminants penetrating into critical components like the gas pressure regulating station and safety devices in the station. It also prevents contaminants entering the low-pressure gas grid. In the majority of cases, the filter housing contains a cylindrical cartridge that captures and, as such, removes contaminants. As the filter becomes more contaminated, the pressure drop across the filter increases, which can be an indication of the need to replace it. However, past tests have shown that the pressure drop is not a good indicator of the extent of contamination [2]. Therefore, a visual inspection alone will be sufficient to establish whether or not a gas filter needs to be replaced.

The filters are typically very robust, because of which the expectation is that they will only fail if they are excessively full [3]. Also, filters do not break because of the gas flowing through them but because of the contamination and corresponding pressure drop. The pressure difference will only become such that a filter breaks when there are very high levels of contamination. Given the materials used in a gas filter, it is not expected that hydrogen will change the filter or the filtration principle. After all, gas momentum (rho-v^2) stays approximately the same for hydrogen, the velocity of which is three times higher than the velocity of natural gas. Therefore, filters are primarily influenced by the amount of dust present. Hence the assumption that consideration primarily needs to be given to dust transport upstream from the filter.

The filters currently used for gas distribution are sourced from various manufacturers. Some of these manufacturers are no longer trading, having merged with other companies, or have stopped manufacturing filters. Suppliers of new filters are very familiar with M-filters and Votech filters. In both cases, these parties supply the G-class filters used in gas pressure regulating stations and gas metering stations.

3. Literature review

3.1 Interesting literature

A great deal of research has been done on the physical process in which a solid is transported by a gas because this has many applications in process technology. Examples of these applications are very diverse; they include the separation of sand from gas in shale gas applications and fluidized bed reactors for nuclear reactors.

In the H100 project report entitled “Transportation of debris by hydrogen flow inside PE pipelines” [4], information available in the public domain is screened and a comparison made between various gases on the basis of physical properties. A number of theories on the transport of dust in natural gas and hydrogen are outlined too. These theories are not unequivocal as regards the ratios of dust transport in natural gas and hydrogen. Nor have any experiments been done to substantiate these theories further.

The paper entitled “Pick-up, critical and wind threshold velocities of particles” [5] screens information about the transport of solids in fluids. Various theories on pneumatic transport are analysed. What is particularly interesting about this article is the way it shows how various theories and experiments follow a master curve with a defined error margin. The analysis based on Reynolds and Archimedes would seem to apply to gases too. The idea of the critical velocity of the transporting medium also applies when dust is transported in a gas distribution network.

The paper above [4] is closely linked to the paper entitled “On the prediction of pickup and saltation velocities in pneumatic conveying” [6]. The latter shows that there are many theories on the pneumatic transport of solid dust particles. The paper distinguishes between fine particles (0-200 micron) and coarse particles (200-4000 micron) and the correlation of Rizk shows a dependence for the transport of dust for various dust-particle sizes. The paper also shows that the transport of solids may depend on the amount of solids to be transported and different types of solid transport were studied.

The paper entitled “Motion of entrained particles in gas streams” [7] explains the relationship between the Reynolds number and the drag coefficient. It focuses specifically on the acceleration and delay of the gas and the effects this has on dust transport. Given the fluctuation of the velocity in a gas network, this is an interesting subject.

In the paper entitled “Minimum transport velocities of minerals and metallic dusts in exhaust systems” [8], experiments are used to consider the pick-up velocity, terminal velocity and saltation velocity of various solids with different densities. The experiments looked at the velocity at which dusts are picked up by a gas flow, fall out of the gas flow and when they move turbulently through a pipeline. For the purpose of this paper, an apparatus was built in which tests were carried out with air. Correlations were formulated for the various solids, based on density and pick-up velocity.

The paper entitled “On the drag of freely falling non-spherical particles” [9] focuses specifically on the influence of the shape characteristics of a dust particle when it is transported in a different medium. The shape of a dust particle influences drag coefficient C_D (in other words: the resistance coefficient) of a dust particle in a gas and is also strongly dependent on the Reynolds number.

All the papers above contributed to the design of the transparent test apparatus.

3.2 Definition of transparent test apparatus

In separation processes, models are used to decide how much it is possible to separate two media. For example, gas-fluid, fluid-fluid, gas-solid or fluid-solid separation. These processes involve a balance of forces between gravity on the one hand and buoyancy on the other hand. This is described in Stokes' law, which is based on the laminar boundary layer theory, in which the boundary layer around a dust particle in a flow is regarded as laminar. The dust particle in question is perfectly spherical. A brief sketch of the situation is shown in the figure below. See Appendix III for an explanation of the variables in the sketch below and later in this subsection.

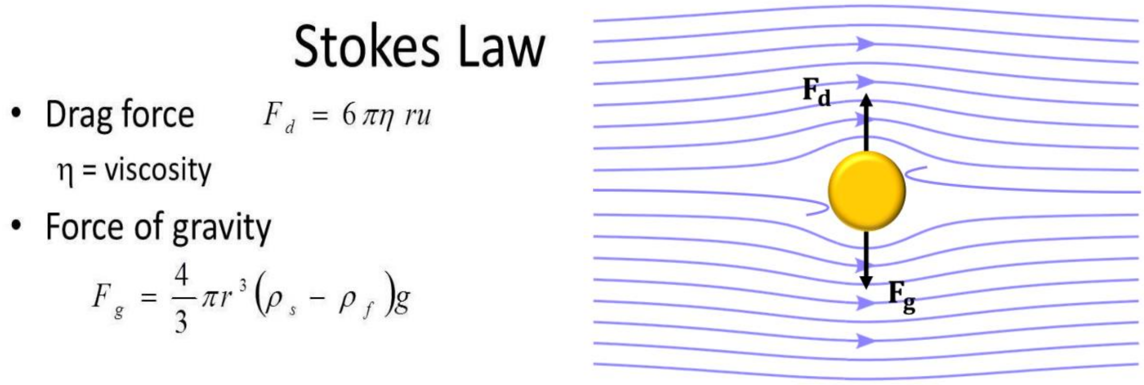

Figure 3 – the forcefield in a horizontal velocity field according to Stokes' law

When the equations above for drag force (in this case, the forcefield in which a dust particle moves) and gravitational force have been defined, terminal velocity (TV) can be determined on the basis of the following equation:

$$Tv = \sqrt{\frac{3gd_p(\rho_p - \rho_g)}{\rho_g}}$$

(Equation 1)

The terminal velocity determines which dust-particle size will move upwards or downwards based on the velocity field. Combined with the stagnant time of a dust particle in a gas network, the forcefield can be used to iteratively determine which dust-particle size can be separated based on the properties of the dust particle and also the medium in which it moves.

Dust present in the gas distribution network is characterised by physical units of measure. The medium (natural gas or hydrogen) and flow field can be used to determine whether a dust particle is in a laminar or turbulent flow field.

The following applies for perfectly spherical dust particles:

$$Tv = \sqrt{\frac{4gd_p(\rho_p - \rho_g)}{3\rho_g C_D}}$$

(Equation 2)

Here, the drag coefficient C_D is a function of the Reynolds number. The sensitivity to turbulence can be defined in line with the figure below (see Perry's Chemical Engineers' Handbook 6-51) [10].

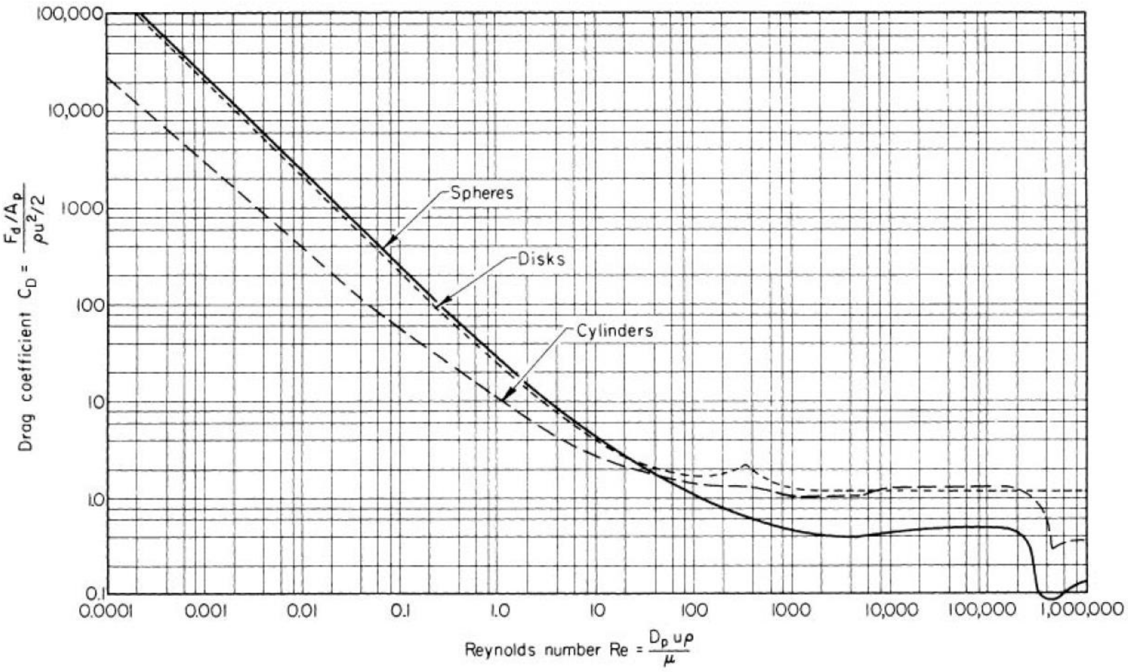

Figure 4 – the forcefield according to Stokes' law

The Reynolds number combined with the chart above can be used to determine the value of drag coefficient C_D for different gases and flow regimes.

As regards the transport of solids, different regimes can be defined on the basis of the drag coefficient based on the Reynolds number. Depending on the Reynolds number, Stokes' law, intermediate law or Newton's law will apply. Newton's law largely corresponds with equation 2. The equation is as follows:

$$Tv = 1.73\sqrt{\frac{gd_p(\rho_p - \rho_g)}{\rho_g}}$$

(Equation 3)

This equation applies to the transport of solids at Reynolds numbers between 1,000 and 350,000.

Based on the variables for the test programme, this theory can be used to determine how long the transparent test apparatus needs to be (in combination with gas velocity) to be able to study the separation of dust particles. See Appendix V for this calculation.

4. Test apparatus

A mobile, transparent test apparatus was designed and built for Step 1 of the test programme. It made it possible to quickly, simply and safely increase and decrease gas flow. The apparatus was used to consider the extent to which theory can be put into practice. The apparatus described here was designed in an iterative process of tests and experiments. The basis, being the visualisation of dust transport, was retained right from the start. This intensive process meant that parts could be added to the apparatus in a number of steps, to improve operation, reproducibility and effectiveness. The apparatus described is the ultimate version. The results described in the sections below were obtained with the apparatus discussed here too.

By using transparent pipes in part of the apparatus, researchers were able to visually ascertain when dust was being transported and how dust acts in different gases.

4.1 Transparent test apparatus

The measurement apparatus is visualised below:

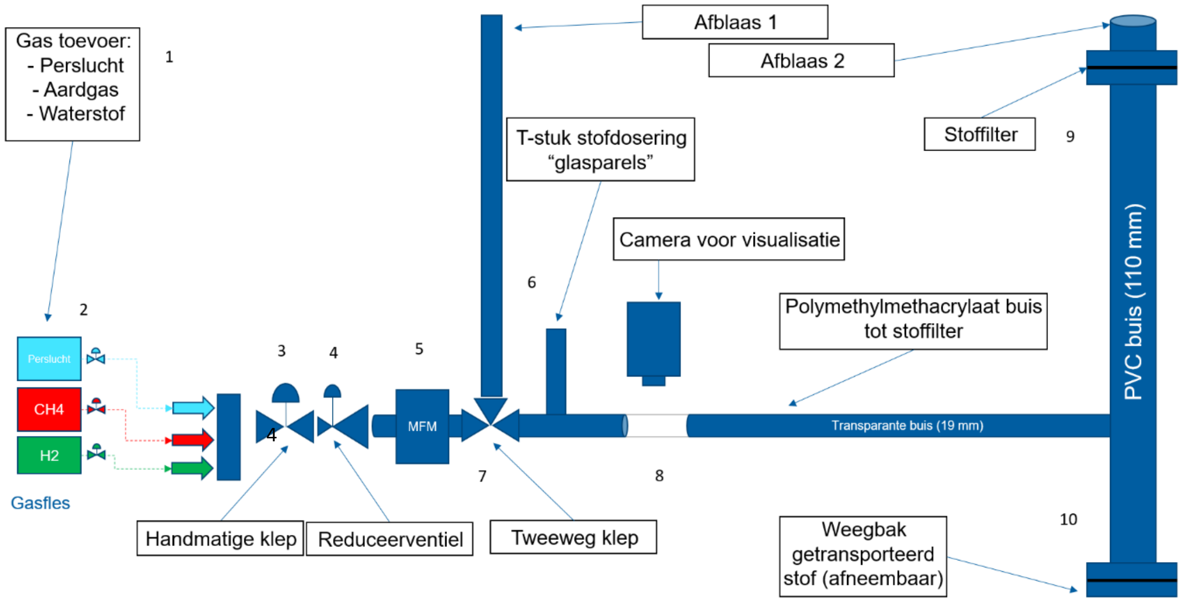

Figure 5 - Schematic representation of transparent test apparatus

1. Gas supply: natural gas, hydrogen or compressed air;
2. Pressure regulator; P_{in} = 200 bar, P_{max} = 8 bar ;
3. Pressure reducing valve (BD-gas - IGA); P_{in} = 8 bar, $P_{u,max}$ = 300 mbar;
4. Manual control valve;
5. Mass flow meter (MFM); compressed air (capacity: 60 m^3_n/h), natural gas, hydrogen (capacity: 210 m^3_n/h);
6. T-piece with a cap for dust dosage;
7. Two-way valve with vent 1 to set flow;
8. Camera for optical insight;
9. Dust filter (110 mm diameter); very dense filter, sandwiched between two PVC flanges. Also vent 2 to vent gas during dust transport tests;
10. Removable weighing tray use to capture transported dust that has settled.

See Appendix VI for an impression of what the transparent test apparatus looks like in practice.

4.2 Type of dust used in experiments

Dust is always present in the distribution network due to the ageing of networks and the work carried out in them. It is often unclear where and in which quantities dust is present. This can lead to unexpected and unpleasant situations [11]. It is expected that the transition from natural gas to hydrogen will result in an increase in gas velocities in the network due to the amount of energy per cubic metre of gas. To include these factors in the research, a literature review was carried out on past experiments that focused on dust transport in distribution networks. In 1977, the municipal companies in Heerlen studied the dust present in a gas distribution network [12]. The main concern was to safeguard both the quantity and quality of gas supply. At the time, the VEG-Gasinstituut studied the solids samples supplied and identified the dust-particle-size fractions too. The majority of these dust particles were smaller than 300 micron. It was found that most of the dust had originated from coke oven gas.

In 1993, research on the use of electric filters in gas distribution networks considered the properties of the dust filtered by installations in the field [13]. Rust was the main component . Tests on these filters were then carried out by GASTEC/TNO at Energiebedrijf Amsterdam.

Both of the ensuing reports showed that dust is primarily made up of iron oxide and sand and is typically approximately 300 micron or smaller in size. Various suppliers were approached to supply dust of this size. Based on the references above, it was decided to opt for the glass beads ($SiO2 > 70\%$) used in sandblasting cabinets. These glass beads were available in the sizes typical of the dust described in the literature above. The dust is well-defined and the glass beads are homogeneous and have a high density, making them very appropriate for the tests outlined above. By making a distinction between fine, medium and coarse dust, the influence of each can be studied effectively.

The photographs below consecutively show fine dust (40-70 micron), medium dust (150-250 micron) and coarse dust (400-600 micron), from left to right. See Appendix V for the exact composition of the glass beads.

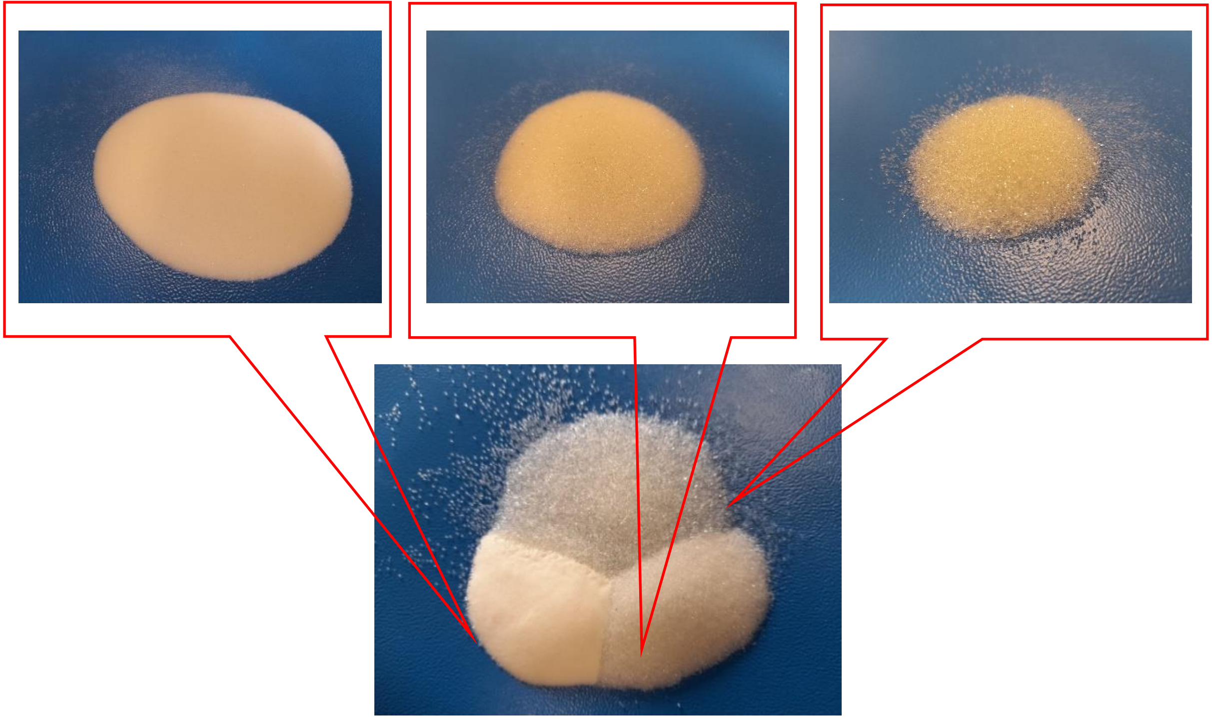

Figure 6 – Top: photographs of the dust chosen (fine, medium and coarse). Bottom: a photograph showing the three sizes next to each other

When the glass beads are examined under a microscope, it becomes apparent that all of the dust particles are almost completely spherical. The microscope also shows that the dust-particle size corresponds well with the specified distribution per type of dust supplied and the dust can be deemed to be homogeneous. Both conclusions are important for the present research because much theory and literature proceeds on the basis of perfectly spherical dust particles for calculations involving empirical equations.

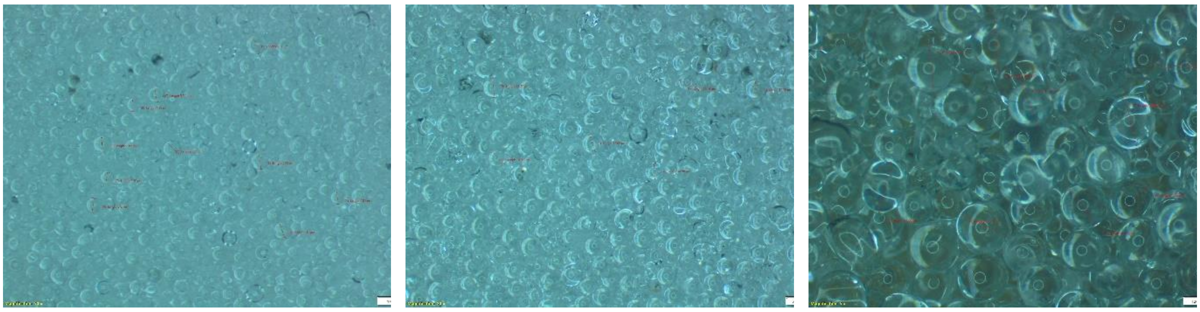

Figure 7 – microscope pictures of the chosen dust (fine, medium and coarse)

4.3 Test matrix

The main objective of the measurement apparatus for Part 1 is to gain a better understanding of how gas is transported by a gas. According to literature on the subject, different variables play a major role:

- The type of gas;
- The temperature and pressure of the gas;
- The type of dust;
- Average dust-particle size and dust-particle-size distribution;
- The velocity of the gas;
- The length of the apparatus (the point between dust injection and the dust filter).

A number of the variables above are tested in the apparatus described. A test matrix is used to ensure this is done on a structured basis. When describing the matrix, we use the term “Terminal Velocity” (TV). This is the gas velocity at which dust is transported along with the gas. If the gas velocity is above the TV, dust transport will take place (dust will move along with the gas flow). If the gas velocity is under the TV, dust will not move (or stay in virtually the same place).

The various steps of which the test matrix consists are defined below:

Test	Gas	Velocity	Dust	Weight	Insight to be gained
Step 1	Air	0 -> TV	Fine	~50 g	The influence of velocity
	Air	0 -> TV	Medium	~50 g	
	Air	0 -> TV	Coarse	~50 g	
Step 2	Natural gas	0 -> TV	Fine	~50 g	Influence of medium
	Natural gas	0 -> TV	Medium	~50 g	
	Natural gas	0 -> TV	Coarse	~50 g	
	Hydrogen	0 -> TV	Fine	~50 g	
	Hydrogen	0 -> TV	Medium	~50 g	
	Hydrogen	0 -> TV	Coarse	~50 g	
Step 3	Air	1.25 TV	Medium	~ 50 g	Influence of time
Step 4	Air	1.25 TV	Medium	~50 g	Reproducibility
	Natural gas	1.25 TV	Medium	~50 g	
	Hydrogen	1.25 TV	Medium	~50 g	
Step 5	Air	1.25 TV	Medium	Variable	Amount of dust
	Natural gas	1.25 TV	Medium	Variable	
	Hydrogen	1.25 TV	Medium	Variable	
Step 6a	Air	1.25TV -> 3TV	Medium	~50 g	The influence of velocity
	Natural gas	1.25TV -> 3TV	Medium	~50 g	
	Hydrogen	1.25TV -> 3TV	Medium	~50 g	
Step 6b	Natural gas	1.25TV -> 3TV	Medium	~50 g	Momentum
	Hydrogen	1.25TV -> 3TV	Medium	~50 g	

Table 1 – experiments with the transparent test apparatus

Step 1 starts with compressed air. The TV of different dust-particle sizes is determined by visually monitoring their transport in the pipe when gradually increasing the gas flow rate. This answers the question of what influence dust-particle size has (expectation: higher TV for bigger dust particles).

In Step 2, the TV of both natural gas and hydrogen is determined, so that the differences between the gases are revealed. Expectation: the TV for air will be approximately the same as the TV for natural gas, while the TV for hydrogen will be approximately three times the TV for natural gas.

In Step 3, a closer look is taken at the influence of time and measurements are taken of the amount of dust separated out by the filter when velocity is set at just above the TV. The object of this measurement is to establish a good time interval for a weight measurement.

Step 4 looks at the reproducibility of measurements. This involves the repetition of identical tests and measurements to identify the extent to which the amount of dust captured is the same in each test.

The object of Step 5 is to establish the influence of the amount of dust available in relation to the amount of dust transported. Will the percentage of dust transported be higher if more dust is added to the T-piece? Expectation: the dust transport percentage will stay the same.

In Step 6a, a closer look is taken at the influence of gas velocity and measurements are taken of the amount of dust transported when the velocity is increased to several times the TV value. Expectation: if the gas velocity is increased, dust transport will increase too. This effect will be stronger with natural gas than with hydrogen.

The object of Step 6b is to substantiate the momentum expectation. This step involves studying whether a similar momentum ($rho*v^2$)[1] of natural gas and hydrogen will result in a similar amount of dust being transported. Expectation: a similar momentum will result in the transport of a similar amount of dust.

4.4 Description of test performance.

The tests started by adding a measured amount of dust to a small-diameter pipe (19 mm ID). The flow rate of the chosen gas is then regulated by a shut-off valve. This causes the gas to flow through the pipe at a defined velocity.

When working through the test matrix, two types of experiment were done, focusing on either the visualisation of dust transport or the weighing of the dust transported.

Where a test was designed to visualise dust transport, the gas flow rate was gradually increased via a manual valve on the upstream side of the mass flow meter (MFM), facilitating the identification of different regimes of dust transport. Whether or not gas is transported through the pipe depends on the type of gas, the properties (density and dust-particle-size distribution) of the dust and its velocity.

Because dust is introduced into the apparatus just once (in batches) via the T-piece, the dust distributes itself across the bottom of the transparent pipe at the start of the experiment. This dust distribution creates a uniform velocity profile above the distributed dust bed and the behaviour of the dust is easy to monitor. The behaviour of the dust in the gas flow was studied halfway between the T-piece and the vertical section (where the filter is located).

After the first dust-transport-distribution, dust distributes itself across the bottom of the transparent pipe. The gradual increase of the gas flow rate creates so-called ‘sand dunes’. Dust particles are picked up and descend again a little further along the pipe. This behaviour is referred to as ‘shifting sand dunes’. It describes how dust is slowly transported through the test apparatus to the weighing section.

Where a test was designed to weigh the dust transported, the gas was vented until the gas velocity was constant. The flow rate is set via a manual valve, followed by a mass flow meter (MFM). A two-way valve is located behind this MFM. In the first position, gas is directed to a vent and this setting is used to set the flow rate. Before turning the ball valve, dust is added via a T-piece with a cap on the top. When this cap is closed and the exact flow rate has been set, the ball valve can be turned and the gas directed through the transparent section.

Dust is transported through the transparent pipe for a specific time interval, after which dust is captured in the weighing tray. This dust is weighed after the test has been completed. The upward gas velocity in the section where the filter is located is so low that dust does not reach the filter (see Appendix V). In the meantime, the transparent test apparatus is cleaned by allowing gas to flow through it at high velocity, by doing which the remaining dust is removed. The weighing tray is returned to its place and the test apparatus is filled with gas again, after which the experiment can be repeated.

5. Measurement results

This section sets out and discusses the results of each step in the test matrix described in Section 4. When doing so, it is also stated whether a visual inspection of the TV was done or whether a weight check was carried out (for example).

5.1 Dust transport in different gases (Steps 1 and 2)

Step 1 of the test matrix starts with experiments involving dust transport in air. These experiments were carried out to visually determine when dust is transported. All of the experiments were duplicated. Before each experiment, approximately 50 g of dust was weighed out. This determined the terminal velocity (TV) of the various dust types (fine, medium and coarse dust). The results are shown as blue bars in the chart in Figure 8.

In Step 2, the experiment above was repeated for both natural gas and hydrogen, thus revealing the differences between the gases. When doing this, the expectation was that the TV of air would be approximately the same as the TV of natural gas. It was also expected that the TV of hydrogen would be approximately three times the TV of natural gas. This expectation was correct for fine, medium and coarse dust. See Figure 8 and Table 2 for the measurement results.

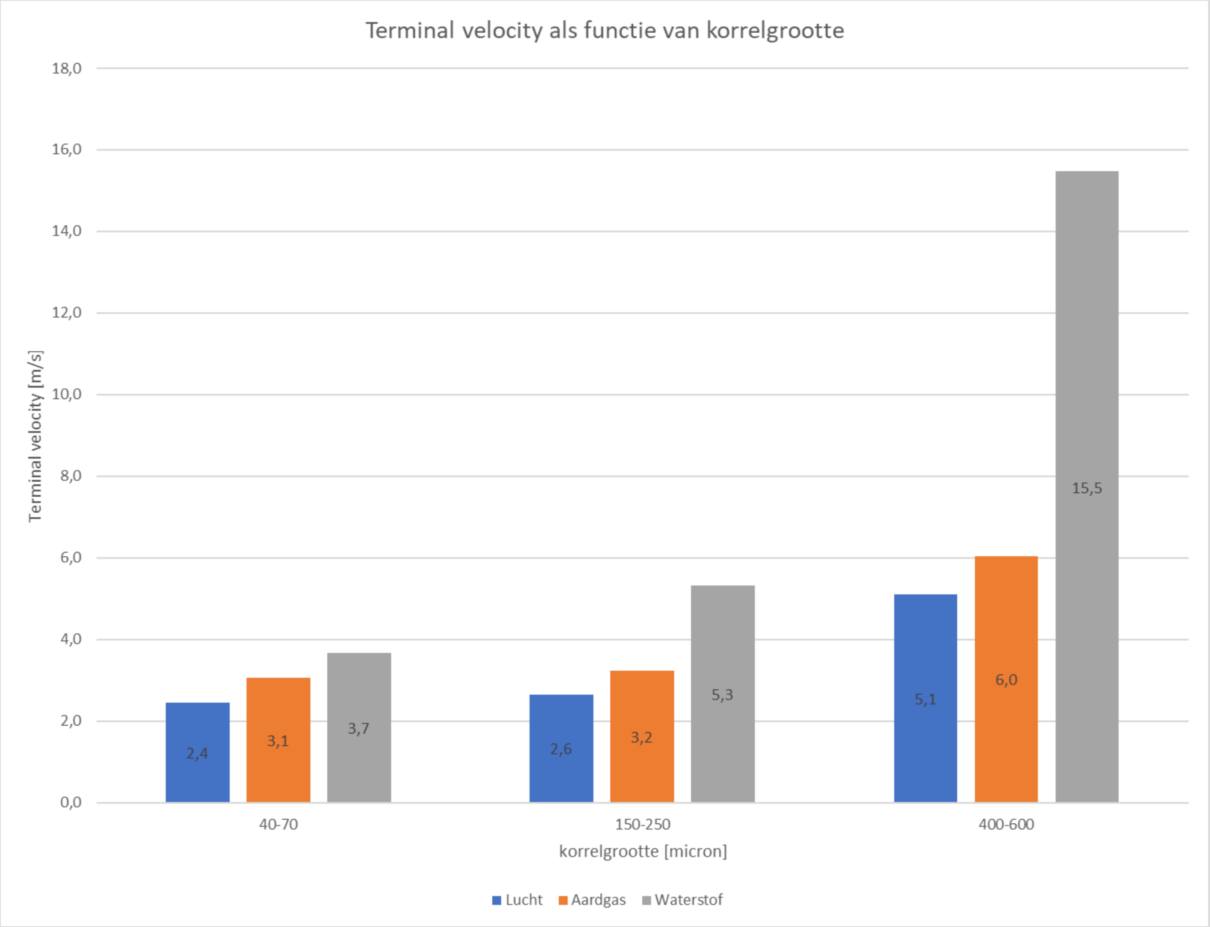

Figure 8 – The terminal velocity (TV) of fine, medium and coarse dust in compressed air, natural gas and hydrogen

The table below provides an overview of the TV of natural gas and hydrogen with different dust types (fine, medium and coarse dust). The ratio between the natural gas and hydrogen flow rate is calculated in this table too. This led to the conclusion that this ratio is not always the same and depends on the type of dust.

	Fine dust	**Medium dust**	**Coarse dust**
Natural gas			
Terminal velocity (TV) [m/s]	3.1	3.2	6.0
Reynolds number	4,539	4,778	8,958
Laminar or turbulent	Turbulent	Turbulent	Turbulent
Hydrogen			
Terminal velocity (TV) [m/s]	3.7	5.4	15.8
Reynolds number	745	1,079	3,138
Laminar or turbulent	Laminar	Laminar	Turbulent
Ratio $TV_{\textbf{natural gas}}$ / $TV_{\textbf{hydrogen}}$	1.2	1.7	2.6

Table 2 – comparison of natural gas with hydrogen

One unexpected effect was the fact that the velocity ratio does not stay the same for different dust-particle sizes. It can be concluded for both fine and medium dust that the ratio between the gas velocity in which dust transport is continuous is much lower than a factor of 3. As shown in Section 3, fine and medium dust are a good representation of the dust present in the gas distribution network. It can be concluded from the results above that more dust will be transported with hydrogen than with natural gas if gas velocity is three times higher for hydrogen than it is for natural gas; this increased velocity is necessary if the same level of energy transport is to be maintained.

5.2 Dust transport and the influence of time (Step 3)

In Step 3, a closer look is taken at the influence of time and measurements are taken of the amount of dust separated out when velocity is set at just above the terminal velocity. The object of this measurement is to establish a good time interval for a weight measurement.

Expectation: the amount of dust captured will depend on velocity, time and dust-particle size.

Five tests were done to study the influence of time. A total of 50 g of medium dust was weighed out for each test. Step 2 revealed the TV value for different gases and dust types. For the purpose of this experiment, 1.25 x TV air was chosen, which translates to a gas velocity of 3.25 m/s.

It was decided to conduct the experiments for 10, 30, 60, 180 and 360 seconds.

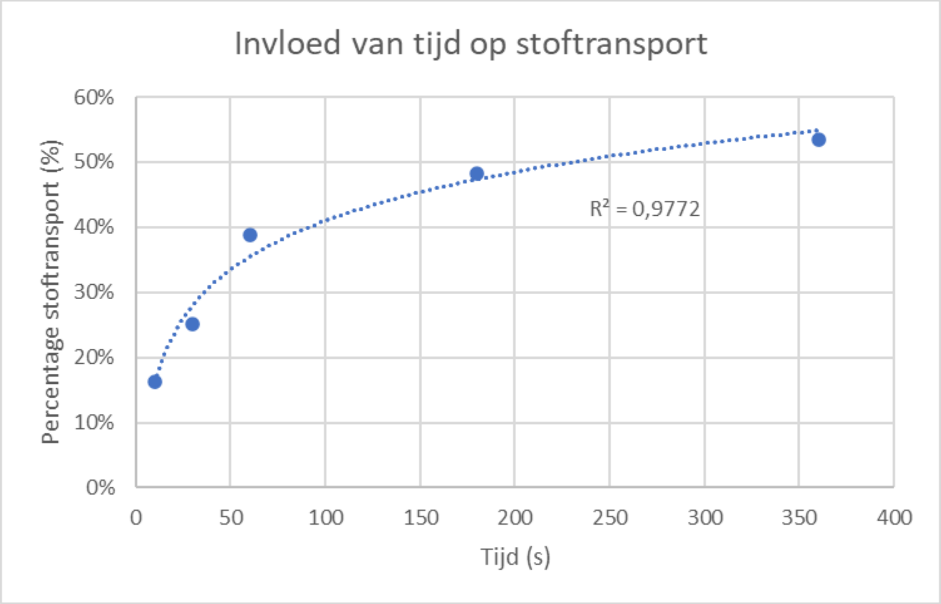

Figure 9 – percentage of medium dust captured as a function of time (in compressed air)

The chart above is possible to construct when the percentage of dust transported is plotted against time. The measurements taken reveal an appropriate trend line (with a high R^2 value (= determination coefficient)). This shows a considerable flattening at higher time intervals. For example, a percentage difference of less than 5% between 180 seconds and 360 seconds.

Bearing in mind the number of experiments to be done, a time interval of 180 seconds was chosen when dust transport involved the transport of a measured amount of dust.

5.3 Dust transport and reproducibility (Step 4)

Step 4 involves the reproducibility of measurements. Identical experiments were repeated with identical settings on different days. A total of 50 g of medium dust was weighed out for each test. The earlier experiments revealed the TV value for different gases and dust sizes. A gas velocity of 1.25 x TV was chosen for all of the experiments, with air, natural gas and hydrogen and dust was transported for 180 seconds. The results are shown in the table below and in Figure 10.

	Air	**Natural gas**	**Hydrogen**
1.25 TV	3.25 m/s	4.0 m/s	6.7 m/s
Test 1	62.8%	30.9%	8.0%
Test 2	62.6%	24.2%	4.8%
Test 3	56.1%	20.3%	7.8%
Test 4	59.8%	28.2%	7.6%
Standard deviation	2.7%	4.0%	1.3%

Table 3 – reproducibility of dust transport with air, natural gas and hydrogen. The test results are shown as a percentage of the original amount of dust transported

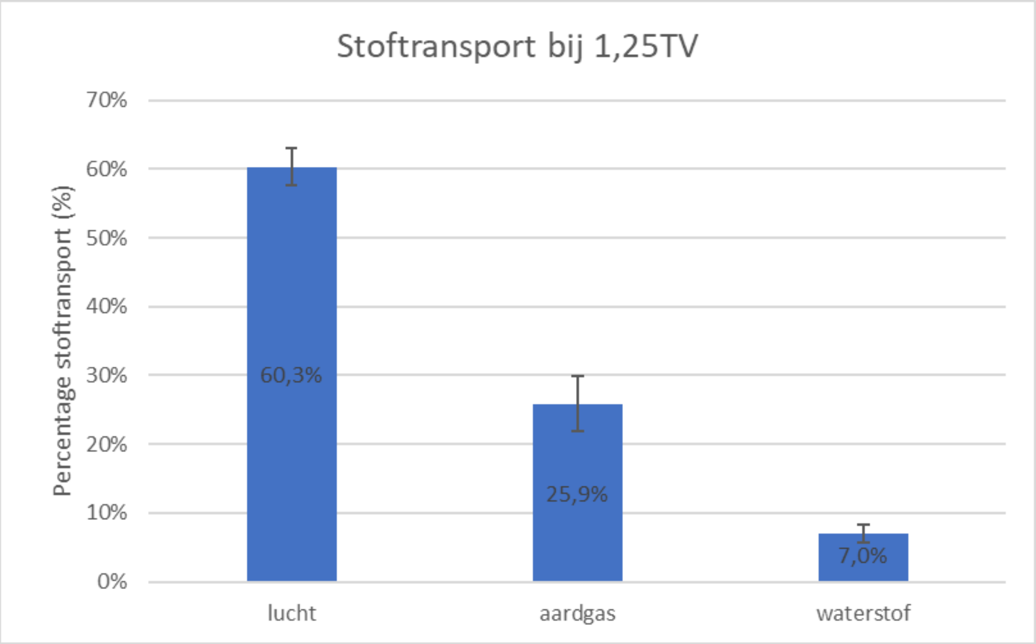

Figure 10 – percentage of medium dust captured for different gases at 1.25 TV

The standard deviation (the black bars in Figure 10) can be used to determine the reproducibility of a distribution measure. Most measurements are around the mean, because of which the standard deviation stays low. It can be concluded from these measurements that the experiments were conducted with a good level of reproducibility.

These experiments also revealed the extent to which different gases (with different densities) transport dust at a gas velocity of 1.25 times the TV value. Less dust is transported when gas density decreases. This suggests a connection between impulse and the amount of dust transported. This will be researched further later.

5.4 Amount of dust present and dust transport (Step 5)

The purpose of Step 5 is to identify a connection between the amount of dust present in the T-piece and the extent of dust transport. Does the amount of dust present influence the percentage of dust transported?

To answer this question, a certain amount of medium dust was measured out for each test in this step. The amount weighed out varied from one experiment to another. For air, conditions meant that just three weights were used: approximately 20 g, 40 g and 60 g. This medium was tested first. The 60-g dosage was found to be impractical because of the dimensions of the T-piece. The maximum dosage was reduced to 50 g for this reason. Weights of 15 g, 25 g, 38 g and 50 g were chosen for natural gas and hydrogen. The linear relationship was checked by redistributing the measurement points (4 instead of 3). These experiments were carried out at 1.25 times the TV value.

The experiment above was conducted for air, natural gas and hydrogen. After 180 seconds, the gas flow was stopped and the amount of dust captured weighed. The results are shown in Figure 11.

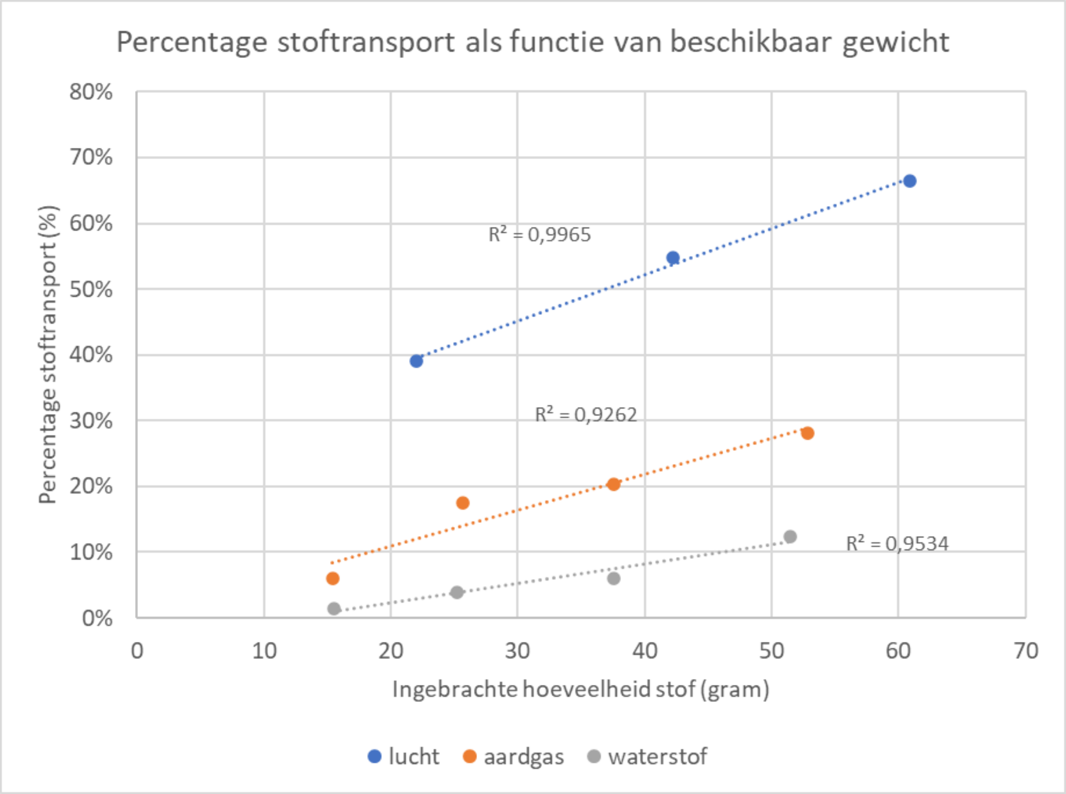

Figure 11 – percentage of dust captured as a function of weight available at 1.25 TV

As expected, air transports the most dust, well away from both natural gas and hydrogen. The same result emerged from the experiments designed to demonstrate reproducibility. It can also be concluded that the amount of dust transported depends on the amount of dust present in a pipe. If more dust is present, more dust will be transported. However, the maximum amount of dust possible to add is limited. The maximum amount measured out in this step (60 g) was less workable in practice, because it took too long to add the dust without spilling it. Given the above, a practical maximum was set (50 g), to ensure sufficient differentiation and also that the measurement method was workable.

One observation was that the method required the two-way valve to be opened in full right at the start of the experiment. The gas, which has a TV of 1.25, distributes the dust present from the T-piece, which happens differently at 20 g than it does at 50 g.

5.5 Dust transport and gas velocity (Step 6)

The object of Step 6 was to identify the relationship between gas velocity and dust transport. A total of 50 g of medium dust was measured out for each test. The earlier experiments revealed the TV value for different gases and dust types. In this experiment, the velocity is gradually increased above the TV value for both natural gas and hydrogen and dust is transported for a total of 180 seconds. The results are shown in the chart below.

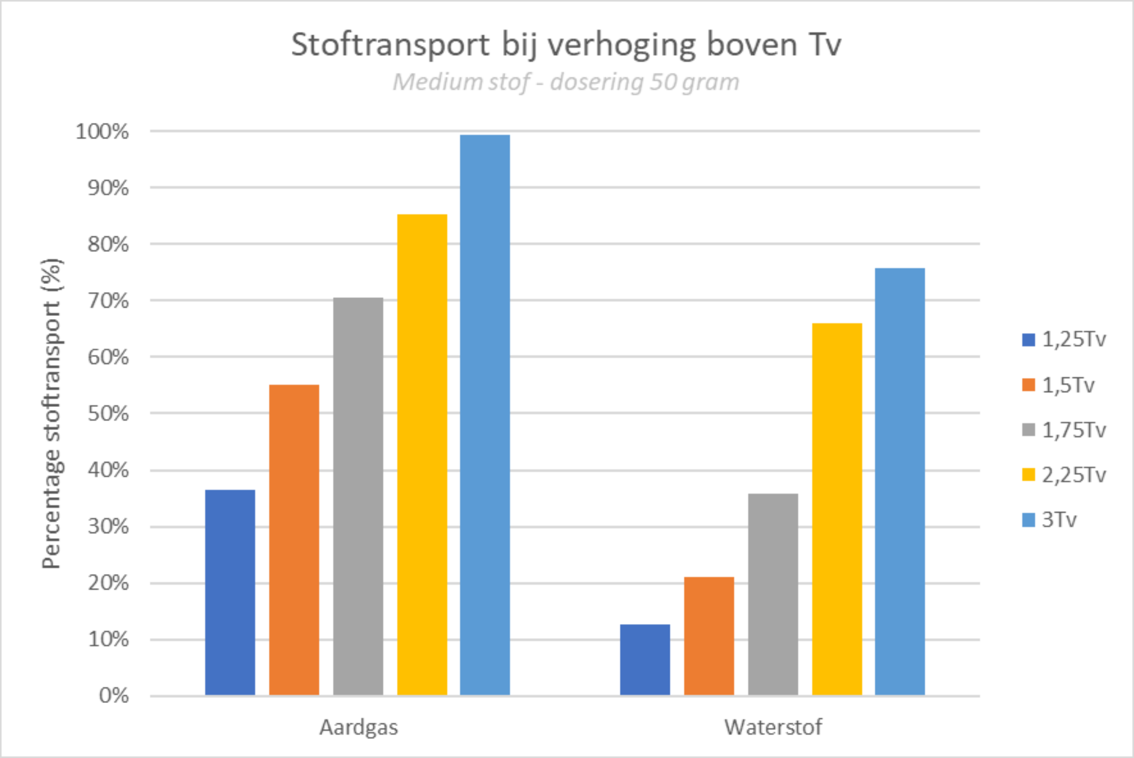

Figure 12 – percentage of dust captured for natural gas and hydrogen at velocities above the TV

This set of experiments showed that dust transport gradually increases if velocity is increased further above the TV value (for both natural gas and hydrogen). However, this increase is far more gradual for hydrogen than it is for natural gas. The percentage of dust transported at three times the TV value is significantly lower for hydrogen than it is for natural gas.

Plotted differently, the result is the chart shown in Figure 13. Extrapolation then makes it possible to conclude that full dust transport with hydrogen (in the allotted time) is achieved at approximately four times the TV value. This corresponds with a velocity of 21.6 m/s. Impulse plays an important role in dust transport but cannot be demonstrated on the basis of the chart below.

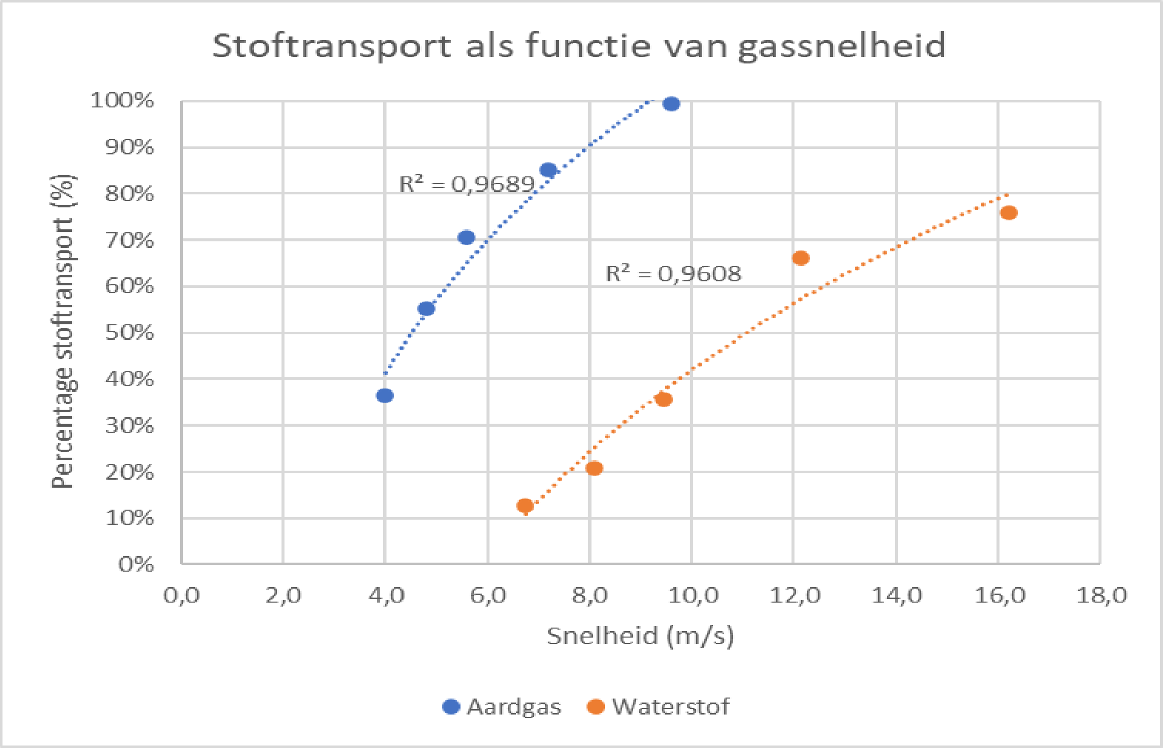

Figure 13 – percentage of dust captured for natural gas and hydrogen at velocities above the TV

If the gas velocities for natural gas and hydrogen are defined by momentum (gas density multiplied by the quadratic gas velocity), a new chart can be constructed that generates a better insight into the relationship between dust transport and impulse.

The gas momentum criterion is used frequently in separation technology and when transporting gases and fluids. It defines momentum as a measure of the force per surface area unit and is used as a measure for matter that is transported by a gas or forces that act on a structure in the flow.

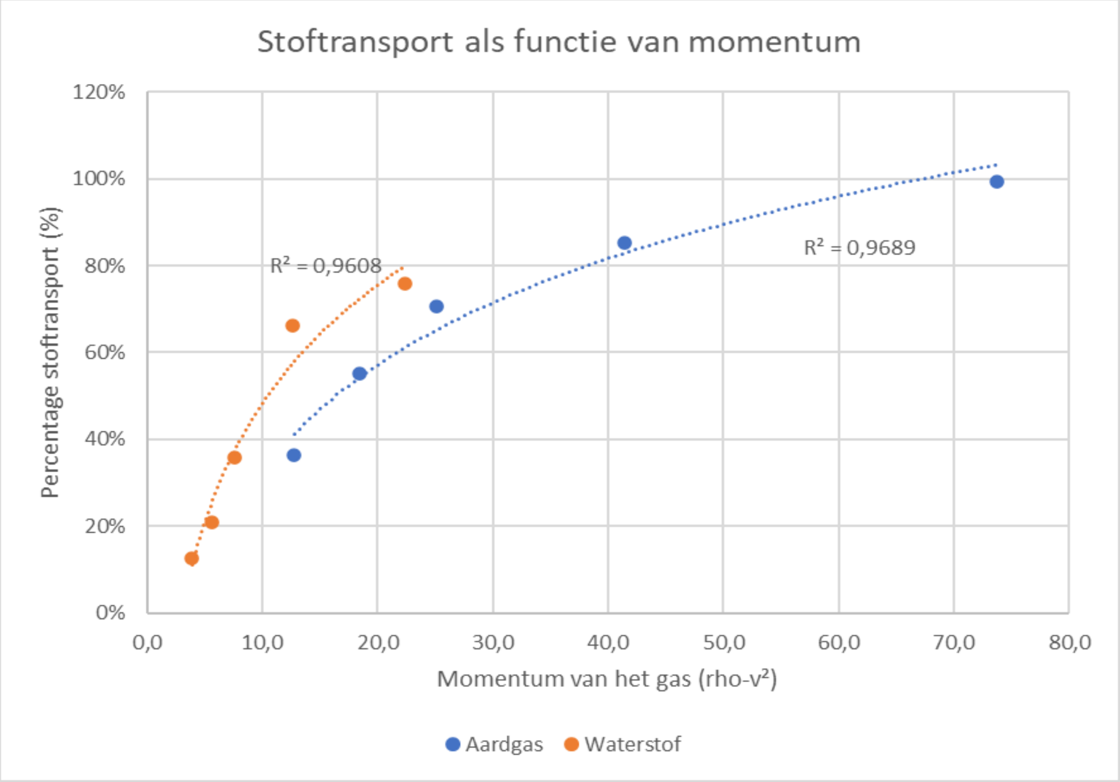

Figure 14 – percentage of dust captured for natural gas and hydrogen as a function of momentum (r ho-v²)

The chart above shows that there could be a relationship between the percentage of dust transport and gas momentum. With a little imagination, a trend line can be drawn through all the values measured for both natural gas and hydrogen (blue and orange). This could point to a relationship between the impulse on a dust particle and the percentage of dust transport, independent of the type of gas. If this *is* true, this could generate valuable information for the estimation of dust transport at other pressures, for example.

Both the impulse of the gas that acts on a dust particle and velocity play a role in dust transport. In various theories covered by the literature review, there is a relationship between the drag coefficient C_D and the Reynolds number. This could be the Reynolds number in a pipe or the Reynolds number of the flow around a falling dust particle in a gas.

Figure 14 applies if the Reynolds number of the gas in a pipe is calculated per measurement point:

TV	Reynolds Natural gas	Regime	Reynolds Hydrogen	Regime
1.25	5,441	Turbulent	1,285	Laminar
1.5	6,529	Turbulent	1,542	Laminar
1.75	7,619	Turbulent	1,799	Laminar
2.25	9,793	Turbulent	2,313	Transition
3	13,058	Turbulent	3,084	Turbulent

Table 4 – Reynolds number for different terminal velocities (TV) for natural gas with hydrogen

A density of 0.833 kg/m^3 and a viscosity of 0.0114 cP are assumed for natural gas, while a density of 0.09 kg/m^3 and a viscosity of 0.0088 cP are assumed for hydrogen.

The data above clearly shows that most dust transport for hydrogen takes place above the TV in a laminar regime too. The flow regime for hydrogen only changes to a turbulent regime at measurements above 2.25xTV.

The analysis above shows that a direct comparison between natural gas and hydrogen is not easy. This is partly because dust transport takes place in a laminar or turbulent regime and the results of these regimes are not possible to compare with each other. Therefore, it cannot definitively be concluded that the same gas momentum acting on a dust particle will lead to the same amount of dust transport.

More measurement data is needed to be able to prove the above definitively. Should there be reason to develop this theory further, it is strongly recommended that more experiments are conducted with hydrogen and natural gas at higher velocities.

When considering all of the results obtained with a view to determining the terminal velocity (TV), it should be remembers that they were determined in atmospheric conditions. If the pressure and/or temperature change(s), the density of the gas changes too, which affects the volumetric flow rate and, as such, gas velocity too.

6. Conclusions and recommendations

Conclusions

The main question in this report is as follows: “Will it be possible to continue to use the current type of dust filter - without any modifications - to safely and efficiently filter dust present in the gas distribution network when the transition is made to hydrogen?”. When answering this question, it is argued that gas filters will not act any differently if the gas flowing through them changes from natural gas to hydrogen. Neither of these gases are viscous, because of which they pass through filters with little drag. Therefore, the question of whether a filter will fail depends primarily on the amount of dust that accumulates on the filter. The amount of dust to be captured by a filter depends on the pipeline network upstream from it. Therefore, any change in filter behaviour will depend primarily on dust movement in the network upstream of the filter.

When designing gas networks, a velocity criterion of 30 m/s is applied in main pipelines, bearing in mind sound production and possible vibrations. In practice, this will not be easy to achieve due to existing overcapacity and the pressure loss permitted. Velocities of 20 m/s are exceptional but possible in short pipeline sections in extreme cold. When using Irene PRO pipeline analysis software to produce a calculation for an existing network at -12ºC, it was found that velocities exceed 5 m/s (for natural gas) in just 10% of the network in a low pressure network. In high pressure networks, this percentage is closer to 50% in extreme cold. However, here too a significant percentage of the network will never achieve a high flow velocity. Therefore, given the TV found for natural gas, it is plausible that there is still dust in the current gas network.

With the above in mind, the present research focused on showing whether there is an increase or decrease in dust transport in a pipeline under the influence of increasing gas velocity. Because the literature review failed to yield an unequivocal answer and relevant experimental work has not been found, a transparent test apparatus was built. Dust transport could then be visualised and characterised.

Following the literature review and additional experiments, researchers were able to define various variables, which then formed the basis for research on the influence on dust transport. For example, research to identify the dust-particle size and density of dust frequently found in the gas distribution network. Three different dust-particle sizes were chosen to characterise dust: fine dust (40-70 micron), medium dust (150-250 micron) and coarse dust (400-600 micron). The reproducibility, time dependence and mass dependence of dust transport at critical gas velocities were identified.

It can be concluded from the above that tests are easy to reproduce, that a time of 3 minutes per test is sufficient to achieve representative dust movement and that a 50-g dosage of dust is appropriate. Based on these tests, a representative ‘basic value’ was chosen for the various parameters: the terminal velocity (TV). This value is typically higher for hydrogen than for natural gas.

The figures above were then used to carry out various tests to gain an insight into dust transport. A number of interesting conclusions and dependencies emerged.

The most important conclusion is that more gas will be transported by hydrogen than by natural gas when the same amount of energy is transported through a pipeline. The most important qualification here is that the truth of the above will depend on both the mean dust-particle size and the density of the dust. This does not mean that the filters in gas stations will capture all of the dust straight away, for example. However, it does mean that this will happen in time.

Although it will take longer for all the dust present to be transported with hydrogen than would be the case with natural gas, all the dust will eventually be transported in the event of velocities above the TV.

Recommendations:

Recommendations for the field
When the transition is made from natural gas to hydrogen in the existing network, it is very probable that increases will not be limited to just the velocities in the network. During the transition process, part of the network will still be operated with natural gas, while the other part will have been converted to operation with hydrogen; it is imaginable that the flow direction in both parts will change at this time. With this in mind, it is expected that more dust transport will take place with hydrogen initially than with natural gas. Depending on the design of the network and the momentary decrease, it is expected that this could initially have a bigger influence on the amount of dust in a filter than the changing flow velocity. The expectation is that a temporary increase in the amount of dust due to a transition to hydrogen would have a similar effect to the one that would happen with natural gas. However, this will need to be the subject of further research.

Therefore, it is recommended that a network/sub-network is flushed at high velocities to remove the dust present from the network. It is also recommended that filters are inspected more frequently after the transition, particularly when a high flow rate passes through the pipeline (during a cold spell, for example).

Recommendation for the NEN 1059 national standard committee
NEN 1059:2019 stipulates that the maximum gas velocity through a filter may not exceed 0.3 m/s. The maximum filter face velocity of the filter housing may not exceed 30 m/s. The basis for these criteria are not discussed in this standard. It is recommended that passages like this are updated to ensure they continue to be practicable for hydrogen distribution. This recommendation will generally also apply to other standards for gas distribution.

Recommendations for further research
The results of this research are an initial indicator that it might be possible to expect more dust in filters when converting an existing gas network from natural gas to hydrogen. As these tests were carried out in atmospheric conditions, it is recommended that they are carried out at 8 bar too, to gain a more detailed insight. The expectation is that few differences will be measured in comparison with the tests at atmospheric pressure. The hypothesis is that gas velocities at which dust transport happens will probably be lower due to the higher density of the gas. This higher density will mean that flows are more likely to be turbulent and that the impulse of the gas on a dust particle will increase too. This research should ideally be conducted with a filter and filter housing that are used in current networks. This would make it possible to identify the effects of increased pressure on dust transport and also criteria for the maximum gas velocities.

The present research showed a possible relationship between the momentum of the gas and the amount of dust transported. At the current time, there are insufficient results to establish this relationship definitively. It is recommended that this momentum theory be the subject of further theoretical and experimental research. It will be important to understand this relationship to be able to make a direct link between individual gases on the one hand and between gases at different pressures on the other hand.

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I Overview of questions for HyDelta WP1B

This work package addresses the following questions:

Material resistance:

- Can the soft components of the regulators and safety devices used in natural gas distribution be adversely affected when switching to hydrogen distribution? (no. 207, see KIWA report GT-200237)

Operation of the station:

- Are the current stations suitable for safely reducing hydrogen gas (the station as a whole)? (no. 206, see HyDelta report - D1B.1 - Gas pressure regulators on natural gas and hydrogen)
- What effects does increasing the velocity have on the overall operation of the station? (no. 213, see HyDelta report - D1B.1 - Gas pressure regulators on natural gas and hydrogen)
- Are adjustments to the housing necessary in order to safely use H2 and, if so, which ones? (ventilation & earthing) (no. 212, see HyDelta report - D1B.3 - Ventilation)

Working safely on and with stations using hydrogen:

- What mitigating measures (VWI) are necessary to commission and decommission a station? (no. 208, see HyDelta Report - D1B.2 - Safety when working on gas stations)
- Is it possible to safely equalise the pressure if a safety device has failed? (no. 209, part of 208, see HyDelta Report - D1B.2 - Safety when working on gas stations)
- Is there a need for a more thorough inspection of filters in gas pressure regulators? This section is specifically about filters; the increased gas velocity can lead to more dirt being transported, which can lead to increased stress on the filters (no. 173, see HyDelta report - D1B.3 - Gas filters)

II Composition of the guidance and sparring groups

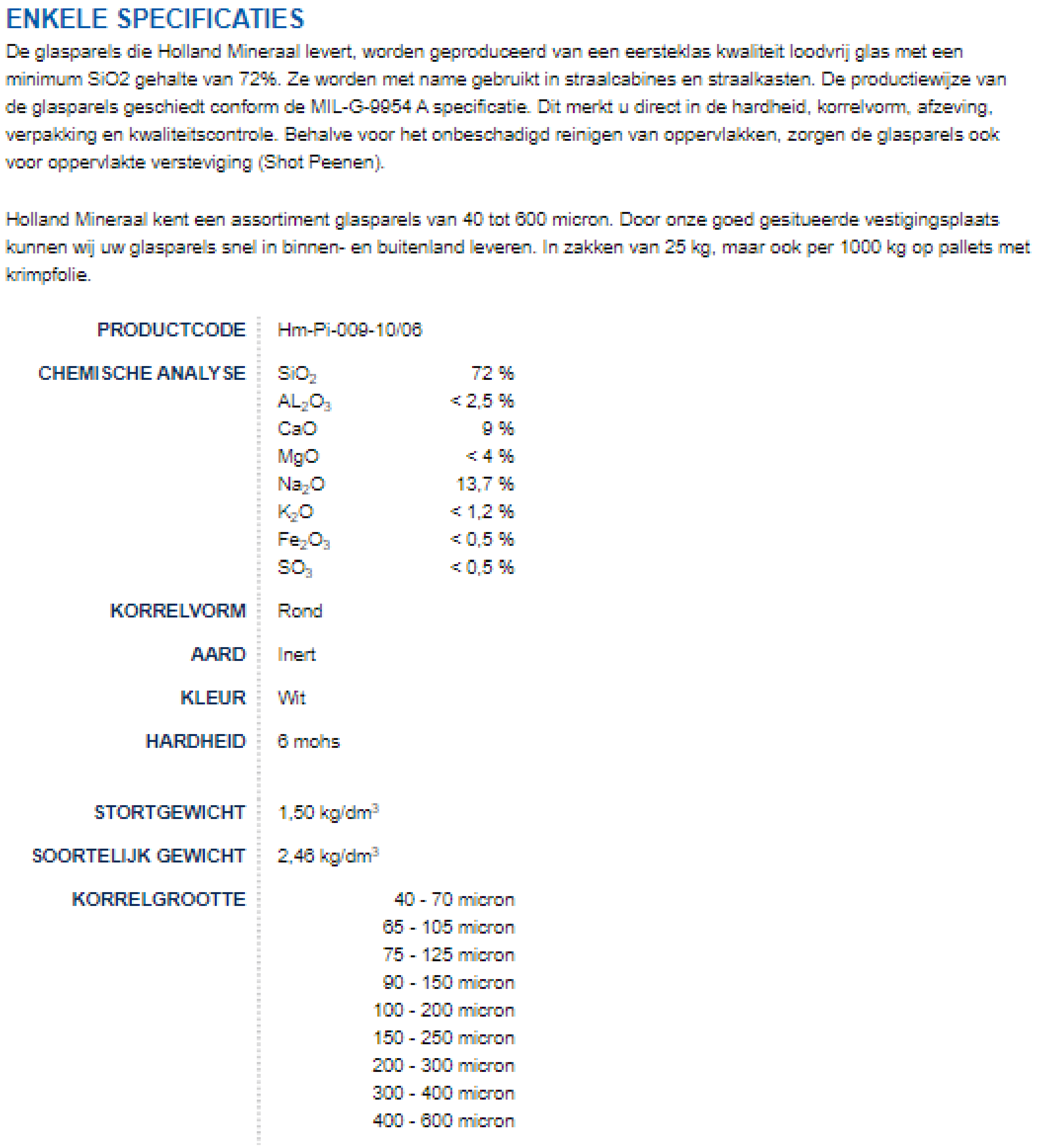
Table 5 – composition of the guidance and sparring groups

Name	**Employer**	**Guidance group**	**Sparring group**
R. van Hooijdonk	Enexis	V	V
J. Jonkman	Rendo	V	V
R. Scholten	Rendo	V	V
P. Verstegen	Alliander	V	V
R. Verhoeve	Stedin		V
J. Voogt	Enexis		V
S.J. Elgersma	Gasunie		V
N. Vermeltfoort	Kiwa Technology		V
S. van Woudenberg	Kiwa Technology	V	V
The guidance group has been assigned a more active role in implementing the sub-research than the sparring group. The sparring group was involved in setting up the test programme and assessing the draft reports.			

III List of terms

Term	Description / explanation
L_{gas} (low calorific gas)	86 vol% methane + 14% nitrogen
Overpressure	Pressure above atmospheric pressure (8 bar corresponds to 9 bar absolute)
$m^3{}_n$	One m^3 at 1013.25 mbar(a) and 0 ^{0}C
CH_4	Methane
F_d	The upward force on a dust particle in a gas flow (N)
F_g	The gravity on a dust particle (N)
H_2	Hydrogen The tests were conducted using hydrogen 5.0 (purity 99.999%)
TV	Terminal Velocity; the velocity at which dust particles start to move with the gas flow.
P_{in}	Incoming pressure in bar(a)
$P_{u, max}$	Outgoing pressure in bar(a)
g	Gravity (9.81 m/s^2)
dp	Particle size of a dust particle (micron)
ρ_p	Density of a dust particle (kg/m^3)
ρ_g	Density of the gas (kg/m^3)
C_D	Drag coefficient (-)
r	Radius of a dust particle (m)
u	Velocity of the gas flow (m/s)

IV Dust composition



ENKELE SPECIFICATIES

De glasparels die Holland Mineraal levert, worden geproduceerd van een eersteklas kwaliteit loodvrij glas met een minimum SiO2 gehalte van 72%. Ze worden met name gebruikt in straalcabines en straalkasten. De productiewijze van de glasparels geschiedt conform de MIL-G-9954 A specificatie. Dit merkt u direct in de hardheid, korrelvorm, afzeving, verpakking en kwaliteitscontrole. Behalve voor het onbeschadigd reinigen van oppervlakken, zorgen de glasparels ook voor oppervlakte versteviging (Shot Peenen).

Holland Mineraal kent een assortiment glasparels van 40 tot 600 micron. Door onze goed gesitueerde vestigingsplaats kunnen wij uw glasparels snel in binnen- en buitenland leveren. In zakken van 25 kg, maar ook per 1000 kg op pallets met krimpfolie.

PRODUCTCODE	Hm-Pi-009-10/06	
CHEMISCHE ANALYSE	SiO_2	72 %
	AL_2O_3	< 2,5 %
	CaO	9 %
	MgO	< 4 %
	Na_2O	13,7 %
	K_2O	< 1,2 %
	Fe_2O_3	< 0,5 %
	SO_3	< 0,5 %
KORRELVORM	Rond	
AARD	Inert	
KLEUR	Wit	
HARDHEID	6 mohs	
STORTGEWICHT	1,50 kg/dm^3	
SOORTELIJK GEWICHT	2,46 kg/dm^3	
KORRELGROOTTE		40 - 70 micron
		65 - 105 micron
		75 - 125 micron
		90 - 150 micron
		100 - 200 micron
		150 - 250 micron
		200 - 300 micron
		300 - 400 micron
		400 - 600 micron

V Calculations for the transparent test apparatus

When building the transparent test apparatus, various variables were used to consider how smart choices could be made on the basis of some simple calculations.

For example, the wish was to design an apparatus with the appropriate length, so that the behaviour of dust could be studied properly. The theory from Subsection 3.2 was used for this purpose.

The diagram below shows how dust particles are transported:

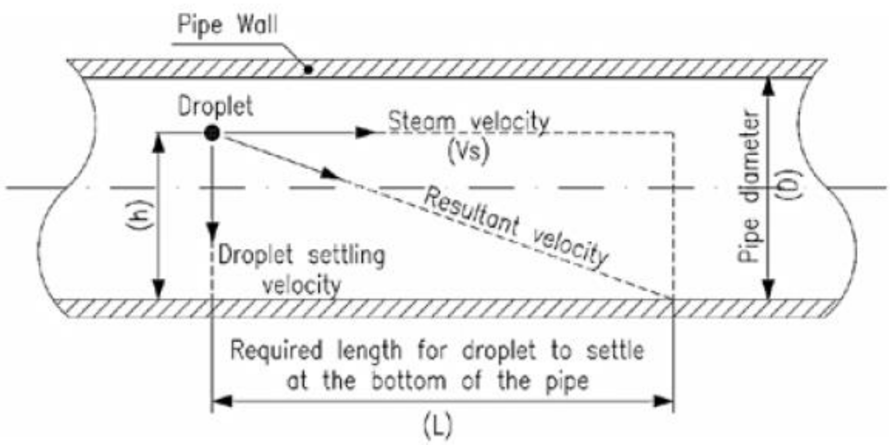


Figure 15 – dust particles settling in a pipe according to Stokes' law

It was decided to use dust with different particle sizes in the test programme. Each type of dust has a minimum and maximum dust-particle size. To avoid dust particles settling in the apparatus, the critical velocity can be calculated on the basis of equation 3. If the velocity of the gas exceeds this critical velocity, dust transport will take place.

If the TV is calculated on the basis of air (density 1.13 kg/m^3) and medium dust (density 2,450 kg/m^3) and a minimum dust-particle size of 150 micron), aided by equation 3, the following will apply:

$$TV = 1.73\sqrt{\frac{g d_p(\rho_p - \rho_g)}{\rho_g}} = 1.73\sqrt{\frac{9.81 \cdot 150 \cdot 10^{-6} \cdot (2{,}460 - 1.13)}{1.13}} = 3.09 \text{ m/s}$$

This shows that the velocity for air must be approximately this value (or higher) for dust transport to be possible.

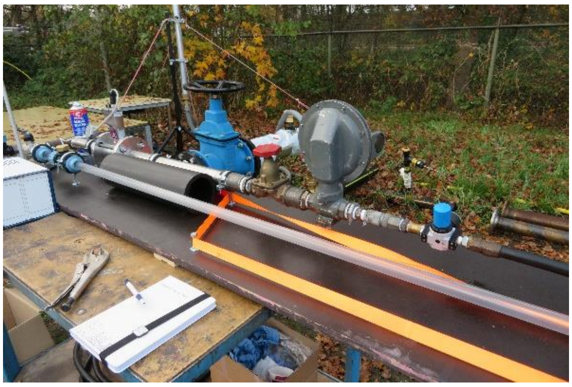
Also, the upward velocity of gas in a vertical pipe must be this value at the very least for dust to be continually transported along with the gas. The velocities in the vertical section of the transparent test apparatus are much lower. This means that no dust will be transported to the filter, because of which the conclusion is that all medium dust will end up in the weighing tray.

A check was also made in line with the boundary layer theory, to ascertain whether the boundary layer was sufficiently small and did influence the experiments. These calculations showed that, depending on the Reynolds number, the boundary layer would be sufficient, but that the tipping point from laminar to turbulent would play a role too.

The calculations above were used to make well-informed choices on the dimensions of the transparent section and the vertical section in which the weighing tray and the filter are located. When carrying out the experiments, the filter was checked for contamination a number of times. This showed that the filter did not capture any dust even at the highest flow rate used in the experiments. As such, these calculations above resulted in a system with the appropriate dimensions.

VI Photographs of the transparent test apparatus

A number of photographs of the test apparatus follow below:



Overview with transparent section

Control valve and pressure reducing valve

T-piece for dust dosage

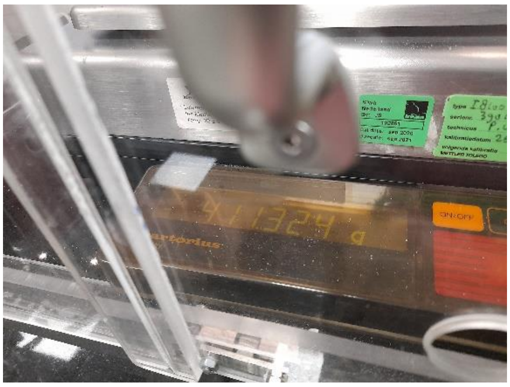
Two-way valve with vent and T-piece

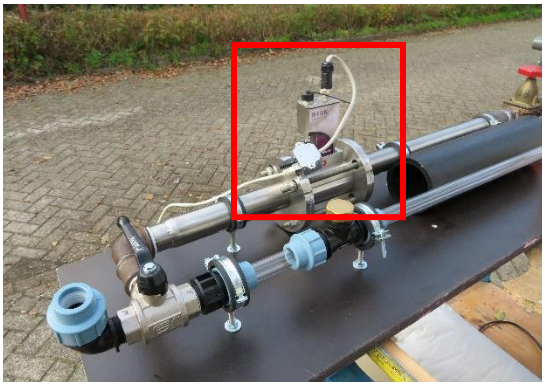
Gas filter and vent 2

Weighing tray


Transparent section and low-velocity section


MFM with control


Precise weighing of dust (including weighing tray)


MFM and two-way valve