Research Article

Rotational Particle Separator as a Compact Gas Scrubber

The rotational particle separator (RPS) is a compact device capable of separating micron-sized droplets from gases by centrifugation. Combined with expansion cooling in a turbine at semi-cryogenic temperatures, it provides the opportunity to remove contaminants like CO₂ and H₂S from natural gas. Potential advantages of this technique are minimum energy consumption and compactness. To demonstrate its potential, an industrial scale RPS prototype is designed and constructed. Experiments are performed to check its overall performance. Both the hydrodynamic performance and the separation efficiency are satisfactory and correspond to theoretical predictions.

Keywords: Centrifugation, Cryogenic processes, Gas scrubbers, Phase separation, Separation techniques

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1 Introduction

Condensed rotational separation (CRS) is a novel separation method for mixtures of gases, which uses elements of cryogenic distillation [1, 2]. A mixture of gases is cooled by expansion through a valve or turbine to a temperature at which one of the components condenses into micron-sized droplets. These droplets are subsequently removed by centrifugal separation using the invention of the rotational particle separator (RPS) [3, 4]. CRS is particularly applicable to systems where reduction in size and weight is advantageous, like floating liquefied natural gas (LNG) production, or the removal of contaminants like CO₂ and H₂S from natural gas [5, 6]. This development is enabled by the availability of efficient cryogenic expanders that are able to work in the condensing area (e.g., GE, Atlas-Copco, Cryostar, Petrogas).

Drawback of the fast reduction in temperature by expansion is the small size of the liquid droplets that are formed. For a gas mixture containing 10 vol.-% or more condensable gas, homogenous and/or heterogeneous nucleation on a time scale of 10 to 100 ms will result in droplets with diameters in the range of 1 to 10 μm [7]. After expansion the droplet diameter hardly changes in time. For example, doubling of the diameter by coagulation takes a few hours [8]. For CRS to be practically achievable it is thus necessary to have a technology that is able to separate micron-sized droplets. The RPS is such a technology.

The RPS is a compact device, devised by Brouwers, for separating micron-sized particles or droplets from gases by centrifugation. The core component of the RPS is the rotating filter element. It consists of a multitude of very small, i.e., few millimeters in diameter, axially oriented channels which rotate as a whole around a common axis. Micron sized droplets entrained in the fluid flowing through the channels are centrifuged towards the walls of the channels and coalesce to form films. At the end of the channels the films break up into large droplets which are collected on the outer wall of the RPS, again under the influence of centrifugation, while the purified gas leaves the RPS. A schematic overview of the operation principle is depicted in Fig. 1.

Compared to conventional techniques, like cyclones, the RPS offers an order of magnitude improvement in either separation performance, equipment volume or energy consumption [2, 9]. The tangential speed in the RPS is the same as in a cyclone (30 to 40 m s⁻¹), while this speed is an order lower than in a compressor or turbine. As a rotating machine, the design of the RPS can be compared to a standard low pressure pump. Reliable technical solutions devised for cryogenic pumps can also be used for the RPS. The RPS has many applications like, among others, the separation of oil from water, the cleaning of air for domestic appliances, the removal of ash particles from flue gases in combustion installations and hot gas filtration in the pyrolysis process [10–12].

In this study the RPS is considered for application in the CRS process to upgrade sour natural gas. Measurements on an experimental setup at a flow of 16 · 10⁻³ N m⁻³ s⁻¹, i.e., normal cubic meters per second, have delivered the proof of principle.
However, in practice flow rates from natural gas wells are in the order of 100 N m$^{-3}$s$^{-1}$. Therefore, experiments were performed with a large scale atmospheric prototype, 24 N m$^{-3}$s$^{-1}$ (80 MMscf d$^{-1}$), which proved that the RPS is capable of handling large liquid loading under large flow rates [6, 13]. The operating pressures in these processes are nowhere near atmospheric however, so there is a need to prove that the RPS works under pressure as well. Therefore, in this study an RPS prototype which separates water droplets from an air flow at a pressure of 4 bar is designed and constructed. The experiments performed show the predicted hydrodynamic performance and separation efficiency.

2 Conceptual Design

A design of a rotational particle separator for liquid-gas separation is given in Fig. 2. Gas containing a mist of droplets enters the unit via a tangential inlet. Large droplets are separated in the pre-separator section due to centrifugal forces. The pre-separator acts as a cyclone and collects the droplets in a stationary volute. The liquid leaves through a tangentially connected exit. The gas stream, containing the remaining mist of mainly micron-sized droplets, enters the rotating element. Here, the droplets coalesce to form films which are forced out of the channels due to gravitational and shear forces. For optimal film behavior and minimal pressure drop the flow direction through the element is downward [14].

At the end of the channels (Fig. 2, pos. A) the films break up into large droplets. The outer wall of the rotating element extends in the axial direction beyond the end of the channels to ensure that the solid body rotation of the gas stream leaving the element is maintained. Droplets that rip off at the end of the channels are centrifugally separated from the gas in this rotating field, and collected in a film on the rotating outer wall (Fig. 2, pos. B). This liquid film leaves the gas stream at the end of the extended outer wall of the rotating element towards a stationary volute. The liquid still contains sufficient angular momentum to rotate the film (Fig. 2, pos. C) within the stationary volute [13]. The liquid leaves the unit via a tangentially connected outlet. The inner wall of the collection volute keeps the liquid separated from the product gas flow. This wall prevents re-entrainment of liquid due to splashing in the post-separator.

2.1 Separation Stages

As the flow enters the pre-separator tangentially it starts to swirl. This swirling flow decays in axial direction due to friction. In the current design the pre-separator is quite short however. If the length of the pre-separator is of the same order as the radius, the axial decay of the tangential velocity is less than 1 % [15]. According to Willems [6], the size of the droplets collected in the pre-separator can then be described by:

$$d_{p,50\%\text{-pre}} = \sqrt[3]{\frac{9 \mu_g v_{ax,pre} (r_{pre}^2 - r_{shaft}^2)}{2 (\rho_l - \rho_g) v_{in}^3 L_{pre}}}$$  \hspace{1cm} (1)$$

where $d_{p,50\%\text{-pre}}$ is the diameter of the droplets collected with a 50 % probability, $r_{pre}$ is the radius of the pre-separator, $\mu_g$ is the dynamic viscosity of the gas, $v_{ax,pre}$ is the axial gas velocity in the pre-separator, $v_{in}$ is the velocity of the fluid as it enters.
the pre-separator, \( r_{\text{shaft}} \) is the radius of the shaft, \( \rho_l \) is the density of the liquid droplets, \( \rho_g \) is the density of the gas and \( L_{\text{pre}} \) is the length of the pre-separator.

In the filter element the contaminated gas rotates as a rigid body and flows in an axial direction parallel to the rotation axis. The size of the droplets collected in the rotating element can be estimated using a relation derived by Brouwers [16]:

\[
d_{p,50\%} = \left[ \frac{27 \mu_d \varphi \rho_l}{2(\rho_l - \rho_g) \pi L_{\text{elem}} (1 - \varepsilon) (r_i^3 - r_o^3) \Omega^2} \right]^{\frac{1}{3}}
\]  

(2)

where \( \varphi \) is the volume flow, \( L_{\text{elem}} \) is the length of the filter element, \( r_o \) and \( r_i \) are the outer and inner radius and \( \Omega \) is the angular speed of the element. The correction factor \((1 - \varepsilon)\) is used to correct for the axial flow cross-sectional area that is occupied by the channel walls, thus resulting in a higher gas velocity inside the channels. Experiments under both laminar and turbulent flow conditions have shown that Eq. (2) predicts the separation efficiency sufficiently well for design purposes [17, 18].

At the exit of the channels the liquid films break up into large droplets which are removed from the gas flow in a similar way as in the pre-separator. The diameter of the droplets that are formed at the end of the channels is determined by a balance between three forces. A shear force and centrifugal body force try to rip off the droplet, while the surface tension force pulls the droplet towards the channel wall. This balance is a cubic function, which can be solved to find an expression for the droplet diameter:

\[
d_{\text{p,post}} = \frac{3}{\rho_l \Omega^2 r_o} \left( \frac{\rho_l \Omega^2 r_o \sigma}{3} + \frac{\rho_g C_D \frac{\varepsilon}{4} v_{ax,ch}^2}{256} - \frac{\rho_g C_D v_{ax,ch}^2}{16} \right)
\]

(3)

where \( d_{\text{p,post}} \) is the droplet break-off diameter, \( \sigma \) is the surface tension and \( C_D \) is the drag coefficient, which is approximately equal to 0.44 for a particle Reynolds number larger than 10⁶ [8]. Once the droplet diameter is known, the residence time of the droplet in the post-separator, \( t_{\text{post}} \) can be determined. Combined with the axial gas velocity in the post-separator, \( v_{ax,\text{post}} \), the length of the post-separator can be determined. For a detailed derivation of the droplet residence time and break-off diameter, the reader is referred to Willems [6].

### 2.2 Natural Drive

As a result of the torque impelled by the tangentially entering flow, the filter element will rotate without the help of an external drive, i.e., the element is naturally driven. The resulting rotational speed can be determined by balancing the momentum of the incoming flow with the loss terms, like bearing friction. However, for design purposes it is sufficient to assume that the rotational speed of the filter element at its outer radius will eventually match the velocity of the incoming flow:

\[
\Omega = \frac{v_o}{r_o}
\]

(4)

where \( \Omega \) is the angular speed in radians per second. This assumption is valid as long as the momentum of the incoming flow is large enough compared to the friction losses. The loss due to turbulent friction in the gap between the rotating element and the static housing increases significantly if process fluids leak through this gap [5]. It is therefore important that this gap is sealed off properly, and is kept as small as possible.

### 2.3 Power Consumption

In case of natural drive, the energy consumption of the RPS occurs through the pressure drop the fluid undergoes when flowing through the apparatus. This power consumption was investigated in detail by van Wissen [2]. The first source of energy consumption consists of losses associated with the incoming swirl velocity \( v_{in} \), reduction in gas swirl caused by friction at stationary walls, mismatch between swirl velocity and the rotational speed of the filter element and incomplete recovery of dynamic pressure in the outlet. These losses can be expressed as:

\[
\Delta p_i = a_i \rho_g v_{in}^2
\]

(5)

where \( a_i \) is the loss factor associated with swirl. The second source of energy consumption is due to a pressure drop over the channels of the rotating filter element. This pressure drop is described by:

\[
\Delta p_{ch} = \frac{\rho_g v_{ax,ch}^2 L_{\text{elem}} f}{2d_c}
\]

(6)

where \( \Delta p_{ch} \) is the pressure drop over the channels, \( v_{ax,ch} \) is the axial gas velocity inside the channels and \( f \) is the friction factor, which depends on the Reynolds number of the flow. For \( Re < 10^5 \), one can take the Blasius formula [19]: \( f = 0.316 \Re^{-0.25} \) to estimate the friction factor. The total pressure drop over the RPS is the sum of the aforementioned contributions. The total energy loss is given by the product of the volume flow rate and the total pressure drop.

### 2.4 Dimensioning

Using the expressions derived in the previous sections, a prototype separator is designed and constructed. This prototype separates fine water droplets from a 230 m³h⁻¹ air flow at a pressure of 4 bar and a temperature of 23 °C. The setup approximately models a 3.1 N m⁻³ (9.5 MMscf d⁻¹) equivalent installation on a natural gas well, assuming process conditions as presented in [20]: a pressure of 32 bar, a temperature of \(-80 \) °C and a gas composed of 61 mol.-% CH₄, 23 mol.-% H₂S and 17 mol.-% CO₂.

The main design parameter is the diameter of the droplets that are collected with a 50 % probability, \( d_{p,50\%} \), which should be 1.5 μm at design conditions. The diameter of the channels in the rotating element is chosen at 1.4 mm, partly due to availability. The dimensions of the rotating element are chosen as: \( L_{\text{elem}} = 200 \) mm, \( r_i = 42.5 \) mm and \( r_o = 82.5 \) mm (cf. Eq. (2)). In order to get the desired \( d_{p,50\%} \), the angular speed of the rotating element should be about 2650 rpm. To reach this speed at the design conditions, the inlet of the RPS should be
59.5 mm in diameter, assuming natural drive as discussed in section 2.3. The length and radius of the pre-separator are chosen as 53 mm and 107 mm respectively. This leads to a $d_{50\%}$ of 7.8 μm under design conditions (cf. Eq. (1)). The diameter of droplets that are formed at the end of the channels is 179 μm (cf. Eq. (3)). The length of the post-separator is therefore chosen as 40 mm, to make sure that all the droplets are removed from the gas flow. The gap size between the rotating element and the static housing is 0.1 mm.

A disadvantage of the natural drive is the lack of controllability over the angular speed of the element. Especially for the separation efficiency measurements, optimal control over the angular speed is required. For this prototype an external drive is therefore incorporated. It can be used to speed up the rotating element or to slow it down if the velocity resulting from the incoming momentum exceeds the required value. A rendered 3D model of the prototype RPS including an electric drive is depicted in Fig. 3.

![Figure 3. A 3D model of the rotational particle separator including the main dimensions. Dimensions are in [mm].](image)

### 3 Experiments

In order to validate the design calculations for the separator, two types of experiments are carried out: separation efficiency and hydrodynamic performance experiments. A schematic overview of the experimental setup is depicted in Fig. 4.

A control valve, which is actuated by pressurized nitrogen, controls the amount of air coming from the 9 bar air supply. Straight after the control valve, a fine mist of water droplets is generated mechanically by 24 so-called pin jet nozzles. In these nozzles, demineralized water at a pressure of 70 bar is forced through an orifice of 152 μm. The resulting jet subsequently breaks up against a metal pin that is situated right in front of the orifice. A substantial amount of the generated droplets is in the micron range. From the specifications of the nozzle manufacturer it can be estimated that approximately 2.7 L min$^{-1}$ of water is injected at a constant rate.

After the injection of water droplets, the air-water mixture passes a pressure sensor and enters the separator. Here, part of the water droplets are collected and drained to two separate collection vessels with a capacity of 50 L each. Since the vessels are not optically accessible, scales are used to measure the increase in weight of the vessels to estimate the amount of liquid inside. Valves at the bottom of these vessels can be used to empty the vessels from time to time while keeping the vessels pressurized while in use.

When the gas with the remaining droplets leaves the separator it flows through an optically accessible section, called the laser test section in Fig. 4. This section provides the possibility to measure the size of the droplets that passes through by use of a laser diffraction technique, which is explained in section 3.1. The laser test section is equipped with a so-called air purge system, which blows air over the windows to prevent contamination of water droplets from the inside. As the gas leaves the test section, it flows through a globe valve, which acts as a back pressure valve to keep the system pressurized, after which the gas flows out into the atmosphere.

#### 3.1 Separation Efficiency

The separation efficiency of the RPS is determined by use of a laser diffraction device (Malvern Spraytec). This device contains a laser source on one side, and a series of detectors on the other. As the mist of droplets passes the laser beam the Spraytec records two parameters. First of all, it measures the volume distribution. This distribution is obtained as a histogram of volume fractions $\Delta f_i$, distributed over 59 intervals $i$ with droplet sizes ranging from $d_{\text{pi}1}$ to $d_{\text{pi}2}$. Secondly, it measures the entire volume concentration of water droplets. This concentration is measured for two situations: $c$ is the concentration with the separator in operation, while $c_0$ is the concentration measured with a nonrotating filter element. The separation efficiency due to the rotating element as a function of droplet diameter is then given by:

$$\eta(d_p) = 1 - \frac{c \Delta f_i}{c_0 \Delta f_i}$$  \hfill (7)
where $\eta$ is the separation efficiency. Note that this is different from the overall separation efficiency, as even a stationary element has a removal effect due to droplet impaction at the channel entrance [9]. An example of the analysis of a separation efficiency curve is presented in Fig. 5. For a more detailed description of separation efficiency measurements, the reader is referred to Brouwers et al. [18].

Note that the efficiency curve has an unexpected shape at small droplet diameters. This is the result of a division of two very small numbers, at the edge of the volume distribution, where measurement inaccuracies play a large role. Therefore, results at relatively small droplets sizes are disregarded.

An analytical expression for the separation efficiency has been derived for laminar flow through circular channels, assuming a linear flow distribution over the rotating element [16]. In order to compare the measured efficiency with this analytical expression, it is convenient to plot the efficiency as a function of the dimensionless parameter $d_p/d_{p,50\%}$. Since $d_{p,50\%}$, as defined in Eq. (2), is a function of flow rate and rotational speed, there is only a single predicted curve as a function of particle size for all operational settings. For a flow rate of 120 m$^3$h$^{-1}$ and atmospheric operating conditions, the measured and predicted efficiencies are depicted in Fig. 6 for different rotational speeds. The corresponding calculated values of $d_{p,50\%}$ at these speeds are presented in Tab. 1. The results in Fig. 6 show that the measured efficiency corresponds well to theoretical predictions. This proves that the RPS is capable of collecting micron-sized droplets. Furthermore, it can be concluded that the droplet diameter $d_{p,50\%}$ is a good parameter for designing the RPS.

For some reason the amount of droplets leaving the RPS becomes much smaller when operating under pressure. One of the reasons for this could be that the pin-jet nozzles produce less small droplets when operating under pressure, but this could not be confirmed. The exact reason is still unknown, and is a subject for further study. As a result of this, the accuracy of the volume distribution measurement becomes too small to draw meaningful conclusions. Luckily, the entire volume concentration of water droplets is still measured with sufficient accuracy. Therefore, the overall efficiency is introduced as:

$$
\eta_\infty = 1 - \frac{e}{c_0}
$$

(8)

Note that this efficiency is independent of the volume distribution and therefore a more reliable parameter. Using this expression, the efficiency is determined as a function of rotational speed at both atmospheric pressure and a pressure of 4 bar. The results are depicted in Fig. 7, together with a theoretical prediction. This prediction is based on the theory used in Fig. 6. For a detailed description of the theoretical prediction, the reader is referred to Kroes [9]. Fig. 7 suggests that the efficiency becomes somewhat lower at operation under pressure. This trend seems to apply to all gas scrubbers, as shown by Austrheim [21]. Here, the exact reason for this trend is unknown however, and is something that needs further investigation.

### 3.2 Natural Drive

The RPS was designed with the assumption that the angular speed of the filter element at its outer radius will even-
ultimately match the velocity of the incoming flow. To see if this assumption is valid, the rotational speed is measured as a function of the volume flow. Note that the electric drive is removed to avoid braking of the filter element. An electronic proximity sensor is used to measure the rotational speed of the axle assembly. The results are depicted in Fig. 8.

The solid line in Fig. 8 indicates the expected value based on the assumption described in Sect. 2.2. Note that the element needs a certain amount of flow before it starts to rotate. At some point, the momentum of the flow is enough to overcome the static bearing friction. After reaching this point, the influence of the bearing friction becomes less and less as the speed is increased. The difference in speed measured at different pressures can be explained as follows. At a certain pressure, the density of a gas is higher than at atmospheric conditions. Since the momentum of a gas flow depends on the density and velocity of the gas, it is larger when operating under pressure. This increase in momentum results in higher rotational speeds.

3.3 Pressure Drop

In order to measure the pressure drop over the RPS accurately, a differential pressure transducer is installed. This sensor measures the pressure difference between the in- and outlet of the RPS with an accuracy of 0.08 % linearity, repeatability and hysteresis included. The pressure drop as a function of volume flow is presented in Fig. 9. In Fig. 9 the measured pressure drop is plotted and compared to the theoretical prediction as described in Sect. 2.3, with \( a_s = 1 \) and \( a_s = 0.75 \). Note that the predicted pressure drop includes both the pressure loss associated with swirl as well as the pressure drop over the channels. Fig. 9 shows that the prediction with \( a_s = 0.75 \) leads to a good agreement with the measurements. Apparently, about 75 % of \( \rho_g v_{in}^2 \) is lost.

4 Discussion

In this study, an industrial scale RPS prototype was designed and constructed. From the hydrodynamic experiments performed with the prototype, two things can be concluded. First of all, the resulting rotational speed due to natural drive is as high as would be expected during operation under pressure. The design estimation predicts the resulting rotational speed accurately enough. Secondly, the pressure drop has been measured and has been used to constitute a design formula.

The separation efficiency experiments showed that the measured efficiency as a function of droplet diameter corresponds to theoretical predictions when operating at atmospheric pressure. It proved impossible to show this efficiency at elevated pressure because of inaccurate measurements, which were
caused by a dilution of droplets leaving the separator at operation under pressure. The exact reason for this could not be found, and is certainly a subject for further study. However, the overall efficiency experiments performed showed that the RPS is capable of collecting micron-sized droplets, also at operation under pressure.

The next step in the development of the rotational particle separator for cleaning natural gas should be a field trial under real process conditions. The effect of the different operating fluids and temperatures is unclear, and should be investigated in more detail. Meanwhile, the current set-up should be improved to be able to perform experiments at design conditions. The water injection system in particular should be upgraded. Additional tests should be carried out to gain more insight into the effect of elevated pressure.

Acknowledgment

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Symbols used

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Greek symbols

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<td>(\alpha_s)</td>
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<td>loss factor associated with swirl</td>
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\[\Delta \rho_{ch}\] [Pa] pressure drop over the channels
\[\Delta \rho_i\] [Pa] pressure drop due to rotation
\[\Delta \rho_i\] \[m^3 m^{-3}\] volume fraction in interval \(i\)
\[\varepsilon\] [-] reduction of effective cross-sectional area of filter element
\[\eta\] [-] separation efficiency
\[\eta_{50\%}\] [-] overall efficiency
\[\mu_g\] [Pa s] dynamic gas viscosity
\[\rho_g\] \[kg m^{-3}\] density of the gas
\[\rho_l\] \[kg m^{-3}\] density of the liquid
\[\sigma\] \[N m^{-1}\] surface tension
\[\tau_{post}\] [s] residence time of a droplet in the post-separator
\[\varphi\] \[m^3 s^{-1}\] volume flow
\[\Omega\] [rad s^{-1}] angular speed

References