MARANDA – Marine application of a new fuel cell powertrain validated in demanding arctic conditions
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Deliverable 3.1 Humidifier characterisation report

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Summary

A humidifier characterization study was performed to evaluate the humidifier performance in selected operating conditions and to examine the effect of salt on the humidifier performance. The experience by VTT from DuraDemo project is that the measured approach dew point may deviate several degrees from promised values.

Humidifiers chosen to the study were FumaTech Ecomate H20 and Perma Pure LLC FC-600-7000-7PP membrane humidifiers. These humidifiers were selected since FumaTech Ecomate H50 series humidifiers are used by SwissHydrogen in their systems and the Perma Pure has been successfully used by VTT in the DuraDemo project.

Varied parameters in the characterization were airflow and dry side inlet air temperatures, while the inlet air pressure and wet air humidity and temperature were held constant.

Characterization using elevated dry air inlet temperatures showed clearly that the performance of humidifier is affected by dry inlet air temperature. The increase of approach dew temperature (ADT) for the FumaTech humidifier was slightly more than 2 °C when dry air inlet temperature was increased from 60 to 100 °C. The ADT value of the Perma Pure humidifier increased even more, by approximately 6 °C when dry air inlet temperature was increased from 55 to 80 °C. The measured ADT values are higher than stated in the manufacturers' data sheets, indicating that the stated values have been measured in a lower temperature.

Humidifier performance was studied under salt particle loading, simulating operation with unfiltered sea air. In total, a salt amount corresponding to 630 days of operation with sea air was fed to the humidifier. There was no effect on humidifier performance to be seen when comparing to the performance before salt loading. Approximately 80% of the salt fed to the humidifier was trapped inside the humidifier, i.e. the humidifier can partly act as a salt trap, thus protecting the PEMFC stack to some extent.

The results of this study will be utilized in the design and construction of the fuel cell system for the Aranda vessel and Kemira durability test site. From a system integrators point of view, the observed dry inlet temperature effect on the humidifier performance is another reason to use an intercooler for the inlet air. Typically, the main motivation for the intercooler is to protect the humidifier from damaging temperatures (>80 °C for Perma Pure, >110 °C for FumaTech).

Since humidifier performance is a strong function of dry inlet air temperature a water injection in air compressor is an interesting topic of a further study, as it can improve the performance of both compressor and humidifier.

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Contents

Abbreviations and symbols

ADT	Approach dew point (difference between wet gas entering humidifier and humidified stream outlet, or wet in – dry out)
BH	Bubble humidifier
NaCl	Sodium chloride
PI	Pressure sensor
PLC	Programmable logic controller
TI	Thermocouple
HUM	Humidity sensor
T_d	Dew point temperature

1. Introduction and aims with the work

The humidifier solutions were characterized ex-situ prior to system integration. Studied factors were the outlet humidity from the membrane humidifier compared to specifications given by the manufacturer, humidifier performance with high inlet air temperature (dry airflow), and the effect of salt particles in inlet air on humidifier performance.

The aim was to evaluate the performance of commercial humidifier solution in the selected operating conditions. The experience by VTT from national DuraDemo project is that the measured approach dew point may deviate several degrees from promised value. The optimal temperature ranger for dry inlet air is between 35 and 55 °C, according the humidifier manufacturer Perma Pure LLC[1].

The effect of salt contamination on the humidifier performance was studied in the second phase of the work, as particle filtering is never perfect. For example, Freudenberg Filtration Technologies promises only 98% particulate efficiency for their fuel cell filters. This may not be enough in marine conditions with high amount of salt particles in the air.

However, the humidifier may act as a salt particle trap, thus protecting the fuel cell stack. At the same time, sodium and other cations might decrease the water transfer rate of the membrane humidifier. Therefore, the humidifier performance was evaluated before and after relevant sea salt contamination.

2. Experimental setup

2.1 Characterized humidifiers

The fuel cell system planned to be installed at the Aranda vessel and Kemira durability test site use a FumaTech Ecomate H50 membrane humidifier. For ex-situ characterization of its performance, a smaller size humidifier with the same basic design from the same manufacturer was chosen: the FumaTech Ecomate H20 humidifier. The H20 model is designed for approximately 30 kW fuel cell systems, which corresponds to a rated airflow of 1200 – 2500 NL/min. The manufacturer states that its performance, measured as approach dew temperature, is 13 °C with an airflow of 1500 NL/min, but remarks that this is dependent on conditions[2]. Maximum pressure drop over the humidifier is stated to be 75 mbar (at 1500 NL/min).

For comparison, another manufacturer's membrane humidifier was studied. The Perma Pure humidifiers (including FC600-7000 Series) have successfully been used at VTT in other research projects, such as the national DuraDemo project. Thus, a FC600-7000-7PP was chosen for characterization. The manufacturer does not give performance values on this exact model, but for the slightly larger model, the FC600-7000-8PP, values are given. The difference between the two models is that the membrane tubes are 7 inch long in the smaller model and 8 inch long in the larger model, i.e. the membrane tubing is 14% longer in the larger model. Approach dew temperature for the FC600-7000-8PP model is stated as 4 °C with 583 NL/min airflow and 6 °C with 1400 NL/min airflow[3].

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[1] Perma Pure LLC, https://www.permapure.com/products/gas-humidification/fc-series-humidifiers/

[2] FumaTech GmbH, Membrane humidifiers data sheet. https://www.fumatech.com/NR/rdonlyres/0B9A1C7F -5BA6-4409-A003-5C4E79CD61AB/0/FUMATECH _BWT_GmbHMembrane_Humidifiers.pdf, Accessed 11.9.2018.

[3] Perma Pure LLC, FC Series Full Manual With Charts. https://www.permapure.com/wp-content/uploads/2013/08/FC-Series-Manual.pdf. Accessed 11.9.2018.

Figure 1 presents the connections and orientation of the studied humidifiers. In both cases, the gas flows were connected in a counter-flow configuration. The Perma Pure humidifier was positioned with all connections on the same horizontal level, while the orientation of the Fumatech humidifier was vertical with respect of the connectors.

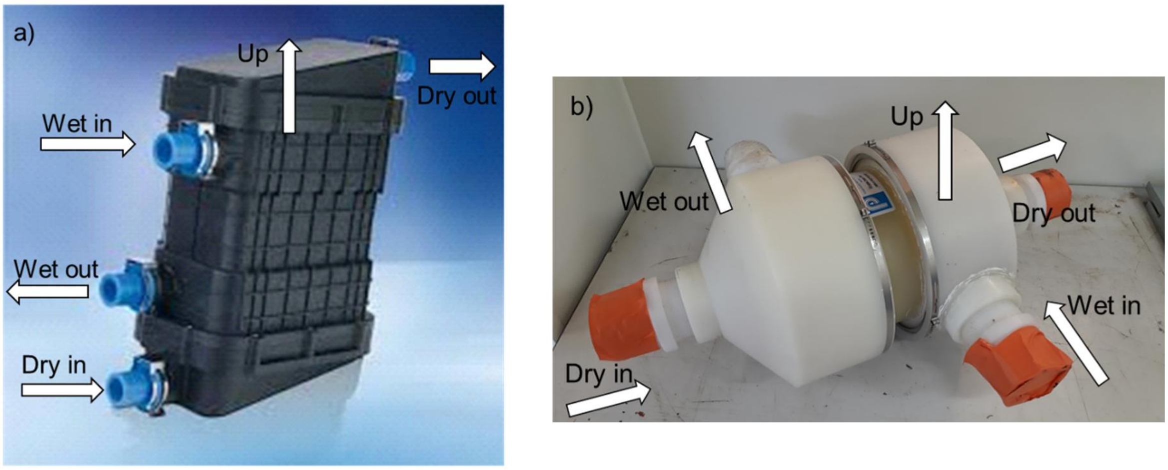

Figure 1: Photos showing the connections and orientation of (a) Fumatech H20 humidifier and (b) Perma Pure FC600-7000-7PP humidifier.

2.2 Test setup

The test bench for humidifier characterization is depicted in Figure 2. The fuel cell stack was replicated by an in-house made bubble humidifier, which humidified the air fed to the wet side of the characterized membrane humidifier. The humidity can be controlled by controlling the water temperature and level in bubble humidifier.

Inlet dry (ambient) air was filtered (Freudenberg) and fed to the membrane humidifier with an Ogura TX12 compressor. The compressor was powered by an ABB motor, which was controlled with an ABB frequency controller. Airflow was measured with a FCI (Fluid Components International LLC) ST75 series mass flow meter.

The inlet dry air temperature was controlled in two ways. A Farnam Tutco FlowTorch 200 air heater downstream of the blower and upstream of the membrane humidifier can be used for heating the dry inlet air. A heat exchanger (Raucell Oy) was used before the compressor to pre-cool the inlet air. Another heat exchanger (Raucell Oy) was used before the exhaust to condensate remaining water vapour from the exhaust air before venting the air.

All lines containing humid air were heated to approx. 5 °C above the dew point of the gas with trace heaters to prevent condensations in the lines. The pressure was controlled with a proportional valve coupled to a pressure sensor. Control, data logging and emergency shutdowns were implemented with an industrial PLC (Schneider)

At all inlets and outlets of the studied membrane humidifier, air temperature, pressure and humidity was measured. K-type thermocouples were used for temperature, WIKA S-10 10000 mbar pressure sensors for pressures and Vaisala HMT337 humidity sensors were used to measure air humidity. Humidity and pressure sensors were calibrated before the measurements presented in this report.

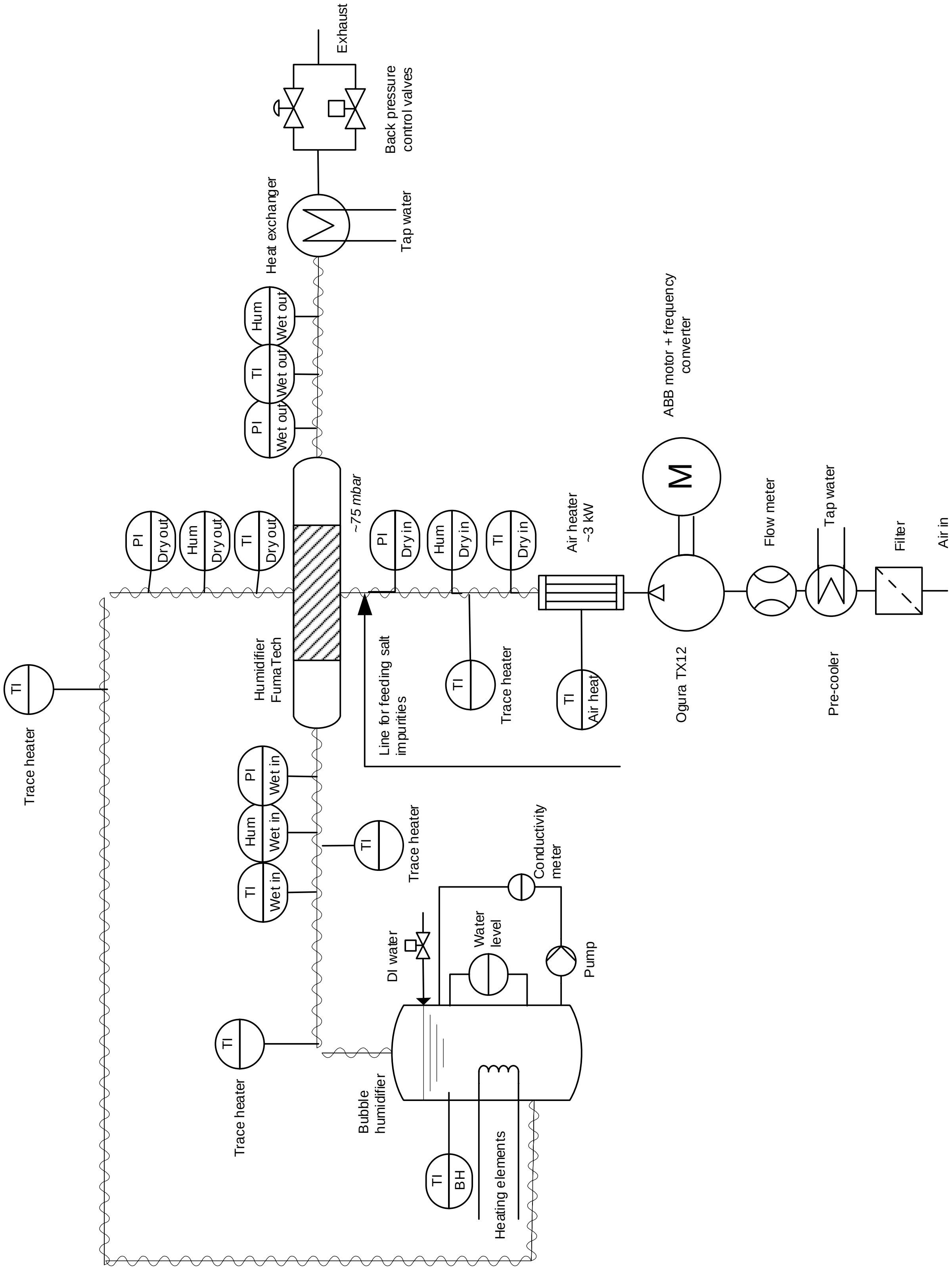

Figure 2: Experimental setup for humidifier characterization. TI stands for temperature indicators, PI for pressure indicators and HUM for humidity sensors. The lines with overlying wave-formed lines depict heated / insulated gas lines.

Salt particles could be introduced to the airflow prior to the membrane humidifier by spraying a NaCl solution to the inlet dry air.

The humidified air from the membrane humidifier was circulated via the bubble humidifier, simulating a fuel cell stack, back to the membrane humidifier as wet air. The bubble humidifier was made of a DN450 pipe and it was filled with deionized water up to approx. 60 cm from the bottom. The water was heated with electrical heaters and the outlet air humidity equalled the corresponding saturation vapour pressure. More details on the evaluation of the humidifying performance of the bubble humidifier can be found in an article by Nikiforow et al[4].

Water salinity was measured using a circulation line with a small-scale pump and a conductivity meter (Bürkert Type 8222, 0.5–200 µS/cm) in the bubble humidifier.

A photo of the constructed test station is shown in Figure 3.

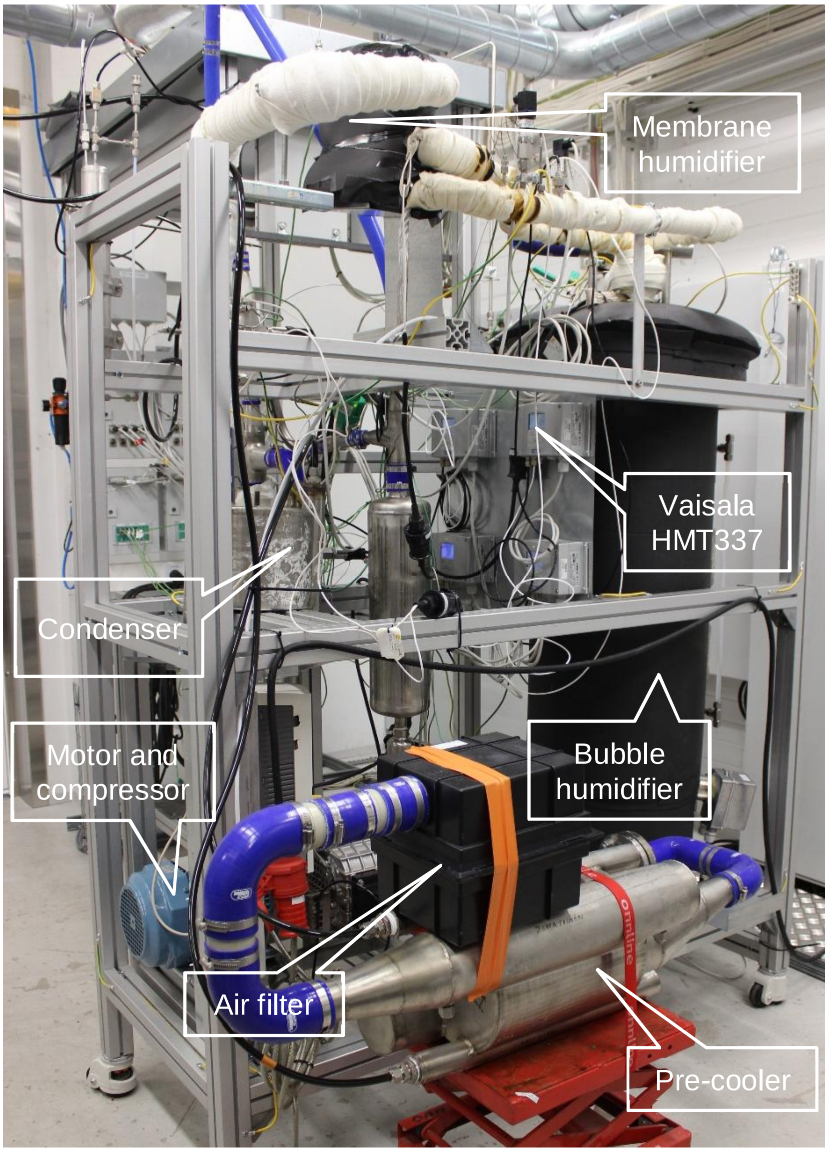

Figure 3: Photo of the constructed test bench with the FumaTech H20 membrane humidifier installed.

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[4] K. Nikiforow, J. Ihonen, T. Keränen, H. Karimäki, V. Alopaeus, "Modelling and experimental validation of H2 gas bubble humidifier for a 50 kW stationary PEMFC system". *International Journal of Hydrogen Energy*, vol, 39, no 15, pp. 9768-9781. Jun 2014.

2.3 Test plan and data processing

The humidifier characterization was done in two steps – first, humidifier performances were characterised with different dry air inlet temperatures. Second, a destructive salt test was performed with Perma Pure when the performance of the humidifier during and after salt particle loading was studied.

2.3.1 Humidifier performance characterization using different dry inlet air temperatures

Varied parameters in the characterization test were the inlet dry air temperature and airflow while the pressure was kept constant:

1) Airflow: 600, 900 and 1200 NL/min
2) Inlet air temperature: 60, 70, 80, 90 and 100 °C [5]

The pressure in the membrane humidifier was kept constant; the average overpressure of the dry inlet and dry outlet side being ~350 mbar in each measurement. This average pressure was controlled with the proportional valve at the exhaust, after the condenser, see Figure 2.

The humidity and temperature at the bubble humidifier outlet (membrane humidifier wet inlet) was kept constant at a level corresponding to the cathode outlet of a fuel cell stack operating with air stoichiometry 1.8 and inlet air dew point of 64 °C. As the bubble humidifier outlet air is saturated, both the gas temperature and dew temperature corresponds to the bubble humidifier water temperature, i.e. 78 °C.

The measured variables (in addition to the airflow and bubble humidifier temperature), were temperature, pressure and partial vapor pressure of water in both the inlet and outlet air to and from the studied membrane humidifier.

The dew point T_d of the humidifier inlet and outlet airflows was calculated similarly as in the Vaisala HMT330 humidity sensors (according to Vaisala HMT330 manual[6]):

$$T_d = \frac{T_n}{\frac{m}{\log \frac{P_w}{A}} - 1} \tag{1}$$

The coefficients T_n, m, and A are depending on the temperature and in this case, values for the temperature range 50–100 °C were used: T_n = 229.1, m = 7.3313, A = 5.9987.

The humidifier performance is described with its ability to transfer water from the wet gas flow to the dry gas flow. This was quantified as the difference between dew point of the wet inlet air and dew point of dry outlet air, and is called *approach to dew point, ADT:*

$$ADT = T_d(wet\ in) - T_d(dry\ out), \tag{2}$$

where T_d is calculated from equation (1). The lower the ADT value, the better does the humidifier perform, as it means that more water is transferred from the humidifier wet inlet gas to the dry outlet gas, i.e. the humidified gas.

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[5] The maximum operating temperature for the Perma Pure humidifier was 80 °C

[6] Vaisala Oyj, HMT330 manual, https://www.vaisala.com/sites/default/files/documents /HMT330%20User%27s%20Guide%20in%20 English%20M210566EN.pdf, accessed 2.9.2018.

2.3.2 Humidifier characterization under salt particle loading

In addition to the effect of elevated dry inlet air temperatures, the effect of salt on the humidifier performance was studied. In a case where the inlet air would be contaminated with salt, e.g. in case of an insufficient particle filtering of the intake air, the membrane humidifier may also act as a salt particle trap thus protecting the fuel cell stack. However, sodium and other cations could decrease the water transfer rate of membrane humidifier.

To simulate such a situation, NaCl solution was sprayed into the dry inlet air to create salt particles, which were fed to the Perma Pure humidifier. The humidifier's performance in different temperatures was characterized before and after salt loading. During salt loading, the airflow was 900 NL/min and the dry inlet air temperature 60 °C. The salt loading was done stepwise as shown in Table 1. During the loading, 9 g/min of a salt solution with 3 m-% NaCl in deionized water was sprayed into the inlet air (salt loading 1.62 g/h). Between each loading step, the humidifier was operated for 30 minutes without salt loading to allow for stabilization and to study the effect of the previous salt loading on the humidifier performance.

In addition, as a part of the salt sprayed into the inlet air adheres to the inner walls of the hosing and pipes leading to the membrane humidifier, these hoses were disassembled and rinsed with DI water between each loading step. The amount of adhered salt and the amount of salt transported to the humidifier was determined by measuring the wash water volume and conductivity. The values in Table 1 correspond to the salt amount that was determined to have reached the humidifier. Similarly, the conductivity of the bubble humidifier water was measured with an online sensor to determine the amount of salt that penetrates through the membrane humidifier.

The corresponding operation time with unfiltered sea air, containing approximately 10 µg/m^3 salt particles, was calculated from the salt amount reaching the humidifier and the airflow, which was kept constant at 900 NL/min.

Table 1: Test matrix for characterization of the Perma Pure humidifier under salt loading.

Step #	Cumulative salt loading / g	Corresponding operation with sea air, cumulative / days
1	0.1	6
2	0.7	50
3	1.4	108
4	2.3	179
5	4.7	365
6	8.2	633

3. Results and discussion

3.1 Humidifier characterization in using different dry inlet air temperatures

First, the humidifiers were characterized over a range of different airflows and air inlet temperatures. The results are presented below separately for each membrane humidifier.

3.1.1 FumaTech Ecomate H20

The FumaTech humidifier's performance was measured with three different airflows (600/900/1200 lpm) and four or five different (60/70/80/90/100 °C) dry air inlet temperatures.

Figure 4 shows a time series of temperatures and humidity of the inlet and outlet airflows, as well as the calculated ADT value in the measurement with dry inlet airflow of 1200 NL/min. It is seen that as the inlet temperature increases, the humidity of the dry outlet air decreases and the humidity of the wet outlet air increase. That is, the performance of the humidifier decreases with increasing inlet air temperatures.

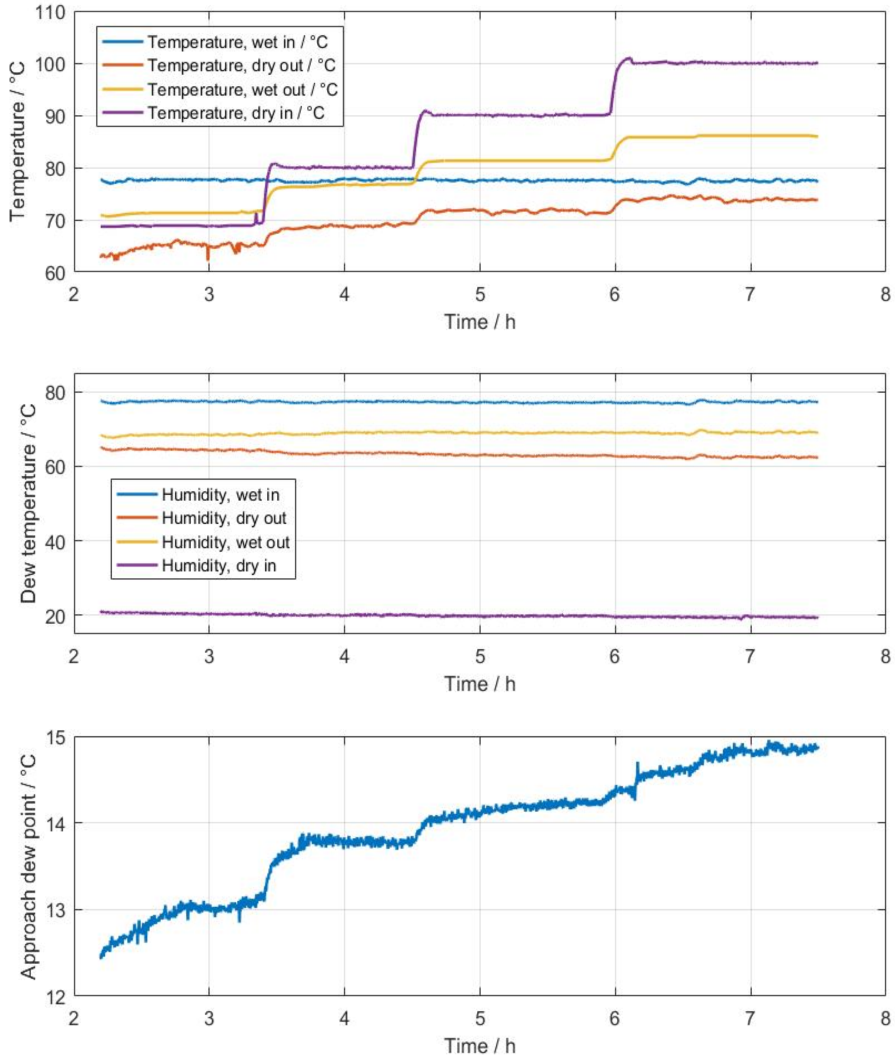

Figure 4: The upper graph shows humidifier inlet and outlet gas temperatures, while the middle graph depicts the measure humidity in the inlet and outlet airflows in terms of dew temperature. The lower graphs presents the humidifier performance in terms of approach dew temperature. Dry inlet airflow is 1200 NL/min.

This behaviour is further illustrated in the ADT plot of Figure 4. It is clearly seen that the ADT value increase as the inlet temperature increase, ranging from 12.5 to nearly 15 °C. The graph also shows that while the temperatures stabilize in some minutes, the dynamic response of the humidity to temperature changes is more than 10 minutes. In fact, when humidifier performance was measured at the highest temperatures (90 °C, 100 °C) steady-state operation was not reached. Therefore, the results of this study may slightly underestimate the drop in humidifier performance. For more accurate estimate, longer measurements would be needed.

In both figures, it is seen that the approach dew temperature increases, i.e. humidifier performance decreases, both due to increases in temperature and due to increases in airflow. In the case of 1200 NL/min airflow, ADT differs approx. 2 °C between the 70 °C and 100 °C inlet temperature. The measured values exceed the ADT values given by the manufacturer, even though the airflow is lower than specified by the manufacturer (1500 NL/min).

By extrapolating the results to lower inlet temperatures, it can be estimated that an ADT of 13 °C (such as given in the specification) could be reached with an airflow of 1500 NL/min at approx. 45-55 °C inlet temperature. However, to reach such inlet temperatures in a real stack system, a relatively large intercooler is needed after the air compressor. As the ADT value is seen to increase with increasing airflow, the need of an intercooler is further enhanced so that the whole flow range of the humidifier can be utilized. In many cases, an intercooler is also needed, as dry air temperature may be higher than the temperature operation temperature allowed for the humidifier.

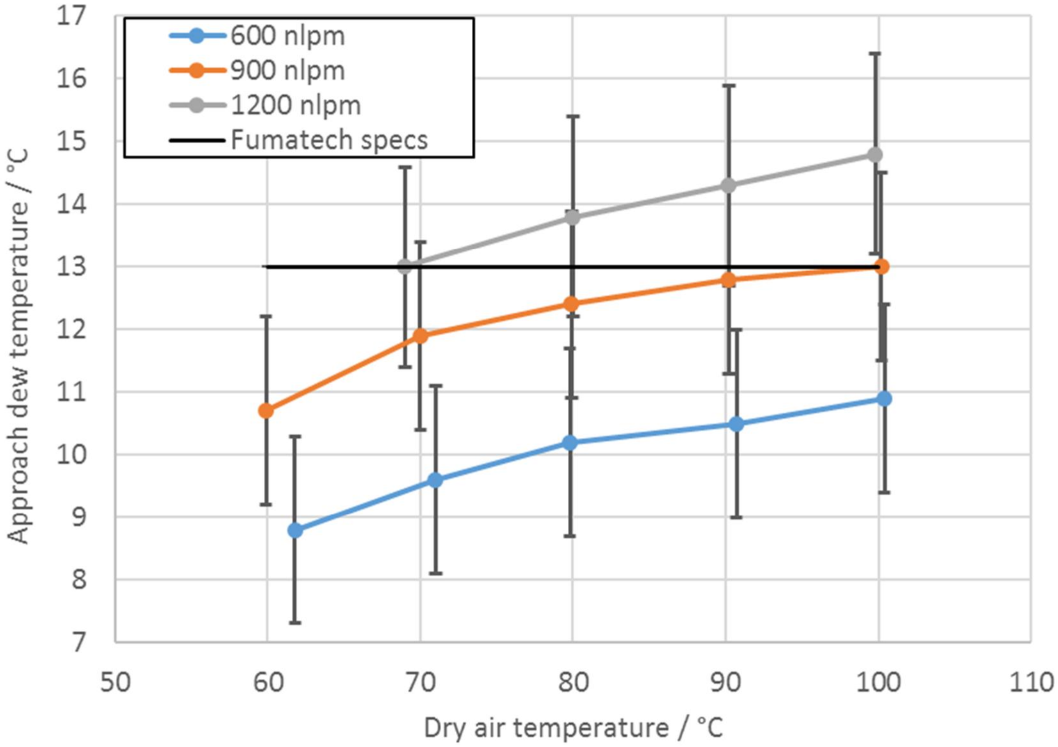

Figure 5: Comparison of ADT of the FumaTech H20 humidifier with different airflows and inlet air temperatures. Measurement uncertainty totals to 1.5 °C.

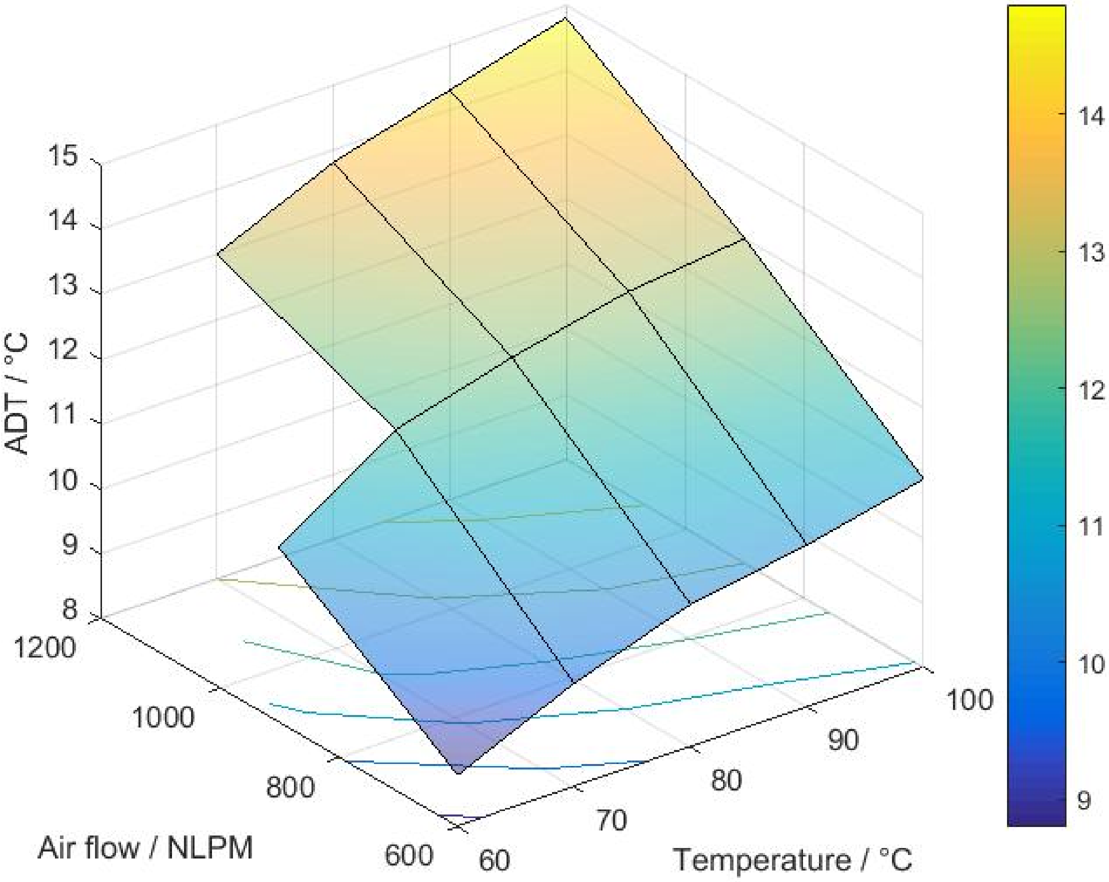

Figure 6: 3D surface diagram presenting the humidifier performance (in terms of approach dew temperature, ADT), as a function of the inlet air temperature and airflow.

Another factor affecting the suitability of the humidifier from a system design point of view is the pressure drop over the humidifier. Figure 7 presents the pressure drops over the wet and dry side of the membrane humidifier with the three different airflows. With the largest airflow 1200 NL/min, the total pressure drop caused by the humidifier is 55 mbar (30 mbar on the wet side and 25 mbar on the dry side). The pressure drop does not seem to be affected by inlet air temperature at these airflows. The effect could be clearer when using higher airflows, close to the maximum of the planned airflows.

The results shown in the graph contain pipe and minor losses from the setup. Extrapolating from the measured values, the pressure drop at 1500 NL/min should be approx. 70 mbar, which is less than 75 mbar as given by the manufacturer.

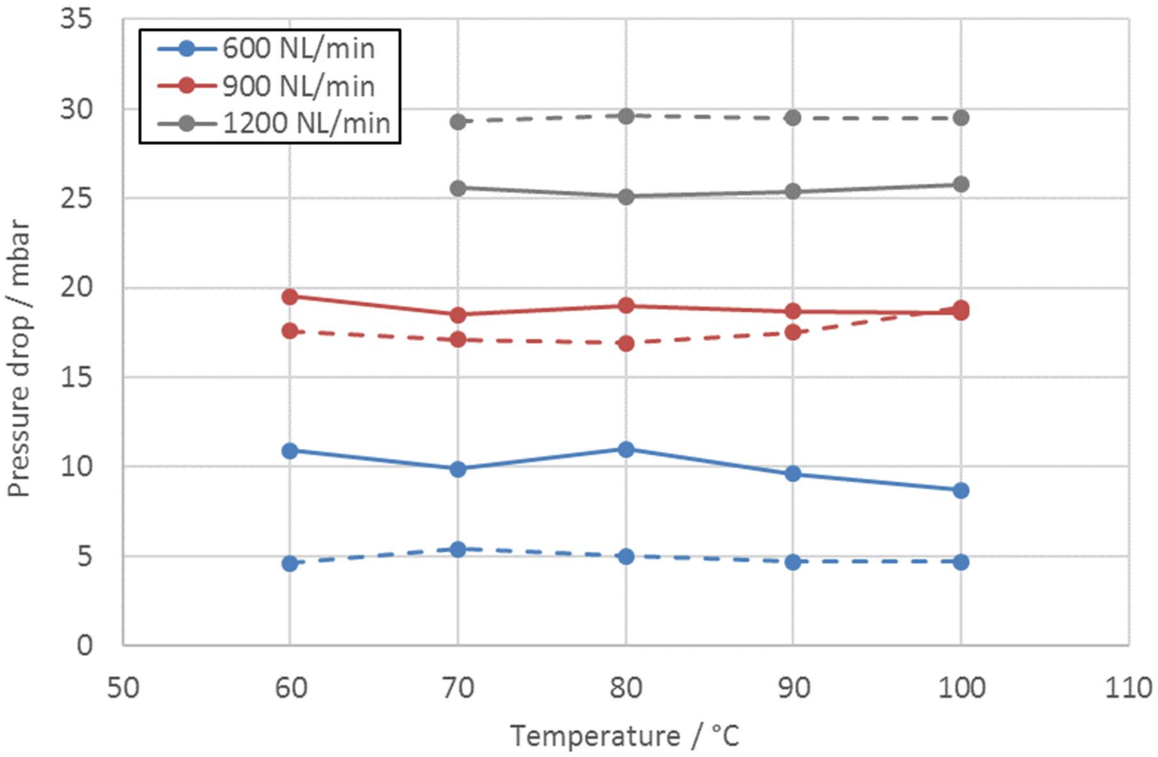

Figure 7: Average pressure drops over the FumaTech membrane humidifier with differing inlet air temperatures. Solid lines depict the dry side pressure drop and dashed line depict pressure drop on the wet side.

3.1.2 Perma Pure FC-600-7000-7PP

The characterization of the Perma Pure FC-600-7000-7PP humidifier was performed with one airflow of 900 NL/min. This was the maximum airflow possible to reach without exceeding the humidifier's pressure limit, which is 350 mbar (inlet pressure). Maximum inlet temperature 80 °C is also significantly lower than the one of FumaTech's humidifier (110 °C).

Figure 8 presents a time series with inlet and outlet air temperatures and humidity, and the calculated approach dew temperature. The middle graph, depicting the air humidity, shows clearly that the dry air outlet humidity decrease when the dry air inlet temperature increase. The lower graph, presenting the calculated approach dew temperature, shows that steady-state was reached at the highest operation temperatures, but not at the lowest temperature (55 °C).

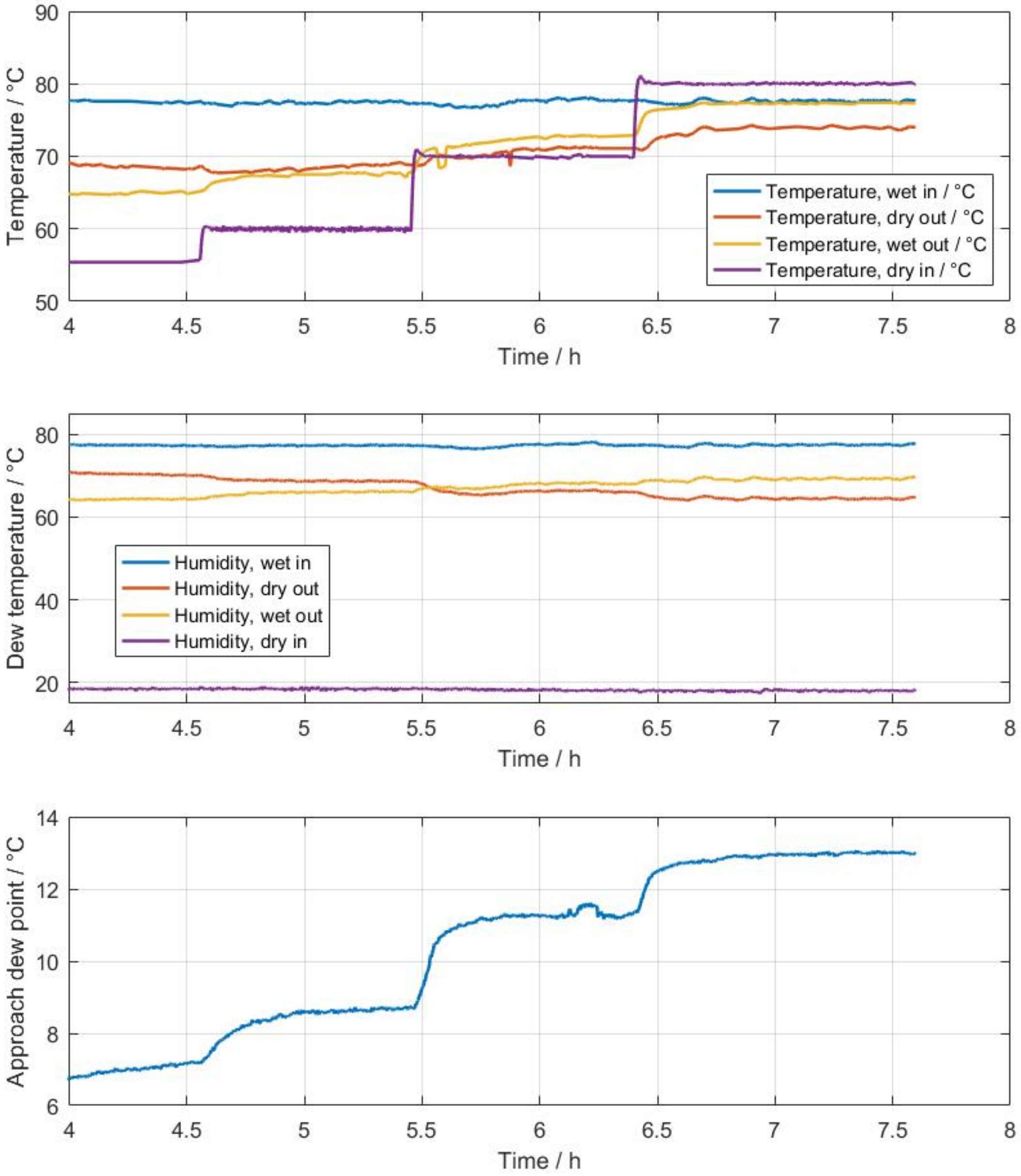

Figure 8: The upper graph shows humidifier inlet and outlet gas temperatures, while the middle graph depicts the measure humidity in the inlet and outlet airflows in terms of dew temperature. The lower graphs presents the humidifier performance in terms of approach dew temperature. Airflow was 900 NL/min.

Figure 9 presents the calculated approach dew temperature for different inlet temperatures. The values range from 7 to 13 °C and the ADT values increase as the inlet air temperature increases. This is the same temperature behaviour as seen for the FumaTech membrane humidifier, where the ADT values range between approx. 10.5 and 12.5 °C in the same temperature range and same airflow.

There is no public information available from Perma Pure on the performance on this particular humidifier model (FC-600-7000-7PP), so it is not possible to compare the measured values against the manufacturer's values. However, for the slightly larger FC-600-7000-8PP humidifier, the manufacturer gives ADT values of 4 °C with 583 NL/min airflow and 6 °C with 1400 NL/min airflow, as described in section 2.1. In FC-600-7000-8PP the membrane tubes are 8 inches, while in the shorter model they are 7 inches. For other Perma Pure models, ADT values are linearly dependent on the membrane tube length. Based on this, ADT values of 4 °C with 510 NL/min airflow and 6 °C with 1225 NL/min airflow can be assumed for FC-600-7000-7PP. For 900 NL/min, ADT values of 5 °C can be estimated.

The measured values in Figure 9 are higher than these values, indicating that the manufacturer's value are measured in a lower temperature, as extrapolation to slightly less than 50 °C would result ADT values of 5 °C. As in the case of the FumaTech humidifier, to utilize the humidifier efficiently in a system, the use of an air intercooler is recommended for the sake of humidifier performance. The maximum temperature (80 °C) of this humidifier would anyway need an intercooler in any slightly pressurised FC system.

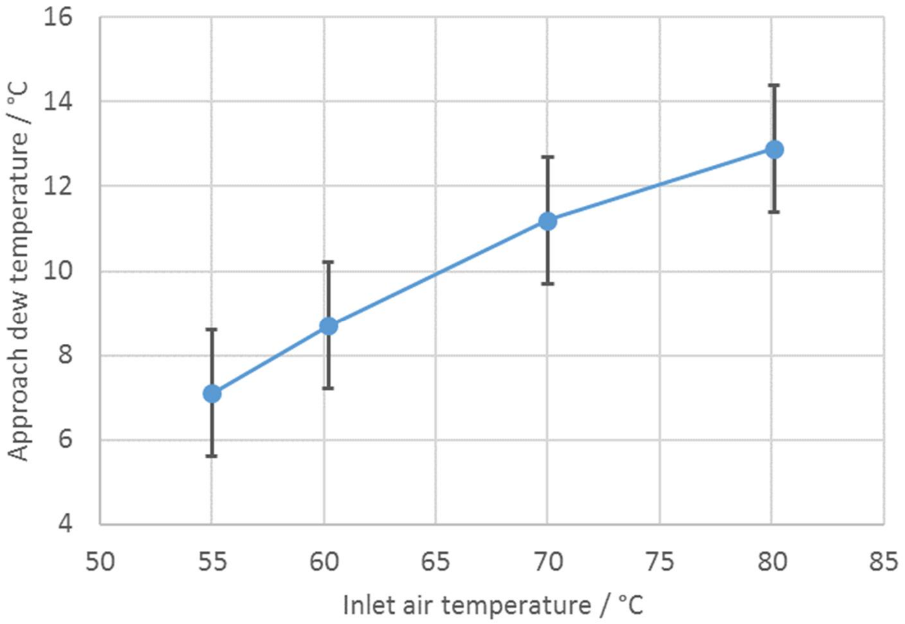

Figure 9: Perma Pure FC-600-7000-7PP humidifier's approach dew temperature at different inlet dry air temperatures. Airflow is 900 NL/min and measurement uncertainty totals to 1.5 °C.

The measured pressure drops over the dry and wet side of the humidifier with different inlet temperatures are shown in Figure 10. The pressure drops are in the same range as for the FumaTech H20 humidifier. On the dry side, the pressure drops are rather constant at 14 mbar, with a slight decreasing trend. The decrease can be explained by the fact that the humidifier performance decrease with increasing temperatures and a smaller amount of water is transported to the dry side, i.e. there is a smaller total amount of gases transported through the dry side at higher temperatures.

On the wet side the pressure drop decrease from 24 mbar to 18 over the measured temperature range, which was not seen in the FumaTech humidifier. The phenomenon can be attributed to formation of liquid water in the channels on the wet side at lower temperatures, as the incoming humid air has a dew point close to 78 °C and the incoming dry air temperature is 55 °C at its lowest. At temperatures of 70 °C and higher, no condensation seem to occur as the pressure drop seems to even out. A closer look on the phenomenon is given in Figure 11 in the form of a time series of the air temperatures and pressure drops during the measurement. It can be estimated that the pressure drop on the wet side evens out to the average value within approximately 5 minutes after a change in inlet air temperature (at temperatures below 70 °C). The detected differences between the FumaTech and Perma Pure humidifiers are probably attributed to differences in humidifier construction and membrane layout.

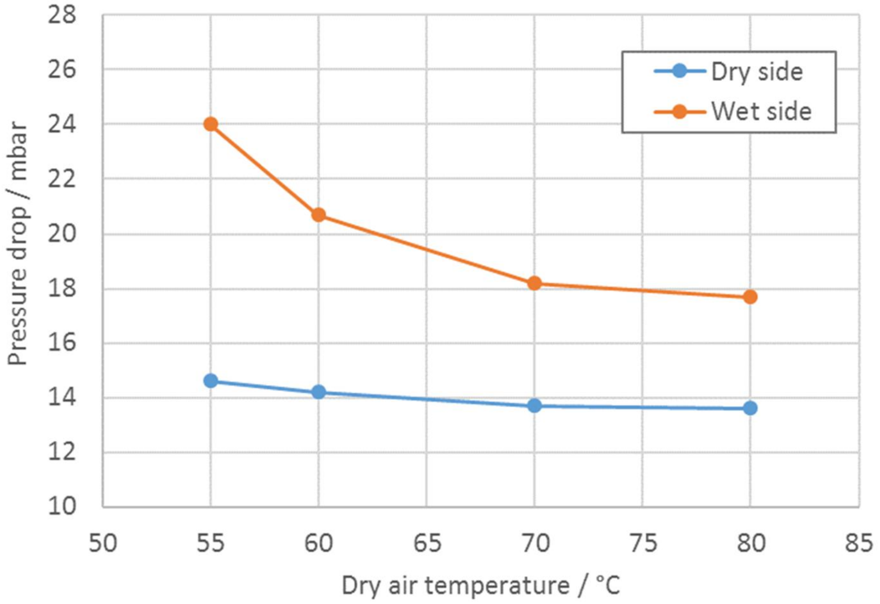

Figure 10: Average pressure drops over the Perma Pure humidifier with differing inlet air temperatures. Airflow is 900 NL/min.

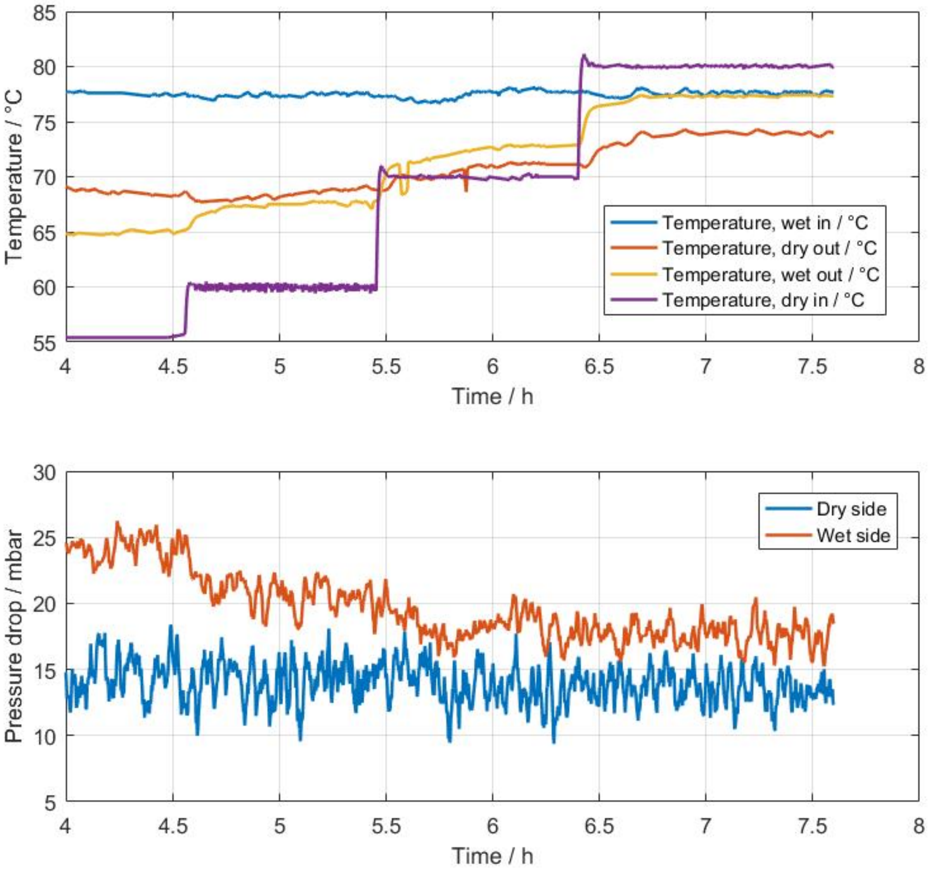

Figure 11: Time series of air temperatures and pressure drop on wet and dry side of the Perma Pure humidifier.

3.2 Humidifier performance under salt particle loading

The Perma Pure humidifier's performance was evaluated under and after dry salt particle loading. During salt particle loading, the performance was measured only with one inlet temperature, 60 °C, but after salt loading, the performance was characterized over a temperature range of 55 to 80 °C.

Figure 12 presents the measured approach dew temperature and the conductivity of bubble humidifier water after each loading step. The values are an average of the 30-minute stabilization time after each loading step. In total, approx. 8.2 g of salt was fed to the membrane humidifier, which corresponds to a cumulative feed of sea air for 330 day, i.e. 21 months. The sea air is expected to contain 10 µg/m^3 salt.

It is seen that the ADT values did not change and thus, the humidifier performance was not affected by the salt feed. However, the conductivity measurement of the bubble humidifier water shows that a part of the salt particles was carried with the dry air through the membrane humidifier to the bubble humidifier, which in this case replicated the PEMFC stack. Especially after the point of 365 days of corresponding sea air loading (4.7 g salt to membrane humidifier) the conductivity of the bubble humidifier (BH) water increased.

In the end of the test, the specific conductivity of the water was 29 µS/cm, which corresponds to a salt amount of 1.5 g. That is, approx. 18% of the salt fed to the membrane humidifier would have been transported with the air through the humidifier to the PEMFC stack. The rest, 82%, was trapped inside the membrane humidifier, which performance was still not affected. The water conductivity results in Figure 12 show also that most part of the salt is slipping in the end of the measurement, indicating that surfaces of the membrane humidifier has become saturated with salt and increasing amount of salt is slipping through.

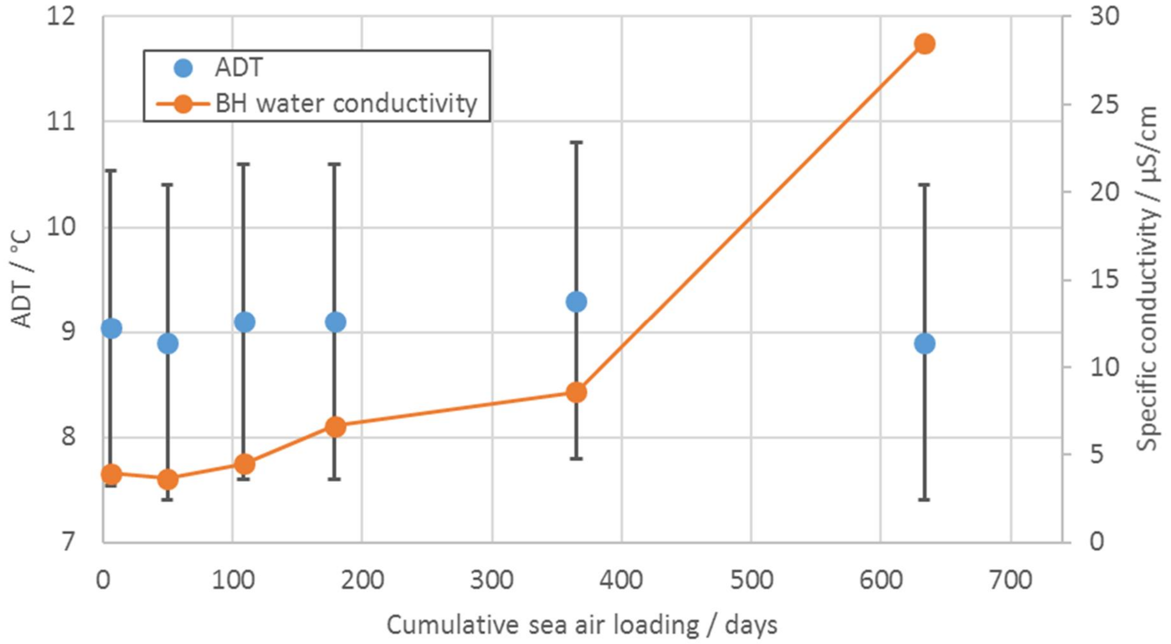

Figure 12: Measured approach dew temperature and bubble humidifier water conductivity after each salt loading step. Inlet air temperature was 60 °C and airflow 900 NL/min.

Figure 13 shows that there is no substantial difference to be seen in the ADT values between the both measurements, when humidifier performance before and after salt loading with different inlet air temperatures are compared. The values fall within the uncertainty limits. These results were already indicated in Figure 12. No recovery of humidifier performance after salt loading was studied, as there was no performance degradation to be seen.

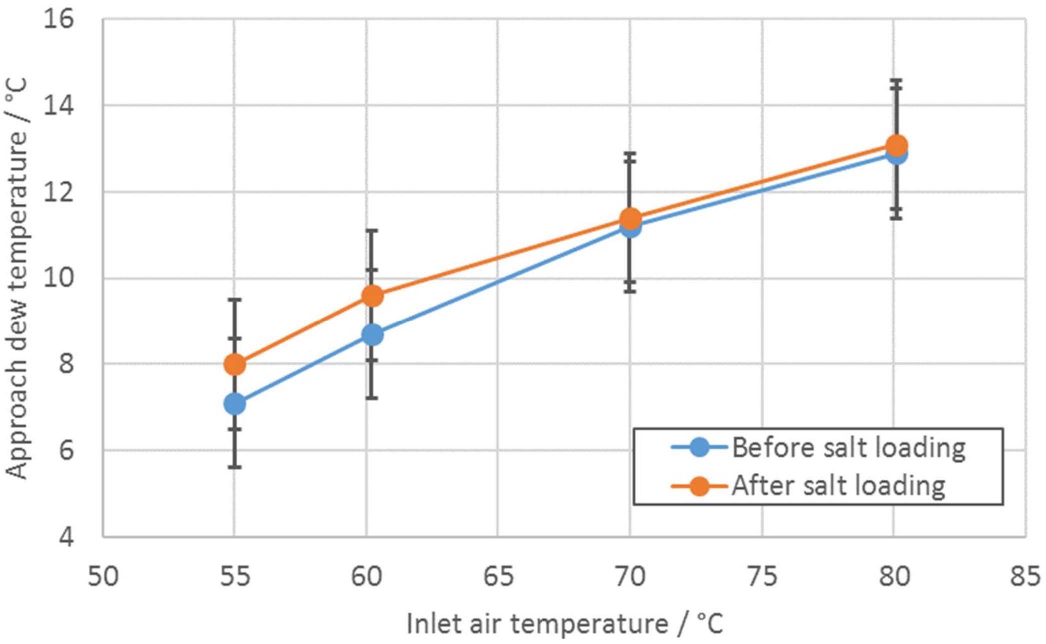

Figure 13: Comparison of Perma Pure FC-600-7000-7PP humidifier performance before and after salt particle loading.

4. Conclusions and topics of further study

Two membrane humidifiers, manufactured by Fumatech GmbH and Perma Pure LLC, were used for the membrane characterisation work. Both humidifiers were characterised with different dry inlet air temperatures and the Fumatech humidifier with several airflows. The Perma Pure humidifier was characterized using destructive salt particle loading, which simulated use with unfiltered sea air.

It was found that dry inlet air temperature clearly affects the performance of both humidifiers. The increase of approach dew temperature for the FumaTech humidifier was slightly more than 2 °C when increasing the dry inlet temperature from 60 to 100 °C. Similarly, the ADT value of the Perma Pure humidifier increased by approx. 6 °C when increasing the dry inlet air temperature from 55 to 80 °C. The measured values were in both cases higher than ADT values given by manufacturers, which indicates that the manufacturer’s values have been measured at lower temperature. Measured pressure drops corresponded to manufacturers’ listed values.

The conclusions of this study are limited to the measurement conditions used. The measurement conditions were selected so that they would correspond as well as possible to the operating conditions of the MARANDA project, taking into account the limitations of experimental setup. For example, wet air inlet temperature was kept constant, while in some systems it might be significantly higher than the dew point of the gas.

The Perma Pure humidifier's performance under salt particle loading was studied. In total 8.2 g of NaCl particles were fed to the humidifier, corresponding to 630 days of operation with unfiltered sea air. The humidifier performance, measured in terms of approach dew temperature, was not affected by the salt particles. The humidifier acted partly as a salt particle trap, deterring approximately 80% of the salt particle fed to it, and the rest were transported with the humidified air to the bubble humidifier, which in a real system would have been the PEMFC system.

The results from this study shall be utilized in the planning and construction of the PEMFC system to the Aranda vessel and the Kemira durability test site. From a system integrators point of view, the observed temperature effect on the humidifier performance is another reason for an intercooler for the inlet air. Typically, the main motivation for the intercooler is to protect the humidifier from damaging temperatures.

For further studying of the humidifier performance a water spray downstream of the compressor and upstream of the membrane humidifier could be tried out. This concept has the following advantages: (i) the water spray would cool down the air entering the humidifier as the water evaporates, thus improving its performance and (ii) it would add humidity to the humidifier inlet air, thus improving the total humidification of the air feed to the fuel cell system. The water spray could also be implemented upstream of the compressor, where it would improve the compressor efficiency by cooling the air as the water evaporates inside the compressor, but there is an inherent risk of corrosion in case liquid water would be present inside the compressor.

Other topics of study could be long-term performance of humidifiers close to the maximum allowable temperature, variation of the wet air inlet temperature and dynamic behaviour of the humidifier.