

Humidity Control
for HV Battery
Systems

Authors

- » Dr. Michael Harenbrock, corresponding author (michael.harenbrock@mann-hummel.com)
- » Dr. Stefan Kunze
- » Stephan Niemeyer

Summary

As HV battery systems for PHEV and BEV cannot be hermetically sealed to avoid housing deformation caused by pressure differences between environment and system interior, pressure balancing is required. Semi-permeable PTFE membranes offer a suitable solution as they let gases pass while holding back particles and liquids. An emergency degassing function can be integrated, reducing overall system complexity. To prevent water vapor condensation at cooling surfaces inside the battery system, an adsorption unit is applied to reduce the risk of corrosion and electric shorts, especially in hot and humid climates. Calculation tools for product dimensioning were developed.

Keywords:

- » safety
- » pollution
- » lithium battery
- » EV (electric vehicle)
- » component

1. Motivation

Climate change is one of the major threats to mankind. Acknowledging this, the COP21 Conference in Paris has agreed on a target of maximum 1.5°C temperature rise compared to the pre-industrial levels to limit the negative effects of global climate change¹. CO₂ emissions from transport globally account for 23% of the total CO₂ emissions². Some countries are already planning to ban vehicles powered by Internal Combustion Engines (ICE) from entering cities or even completely to achieve these targets (e.g. India, Norway, Netherlands)³. As the decrease of battery pack cost is faster than expected⁴, OEMs believe a cost break-even between xEV and ICE which meet the more stringent NO_x and PM_{2.5} emission targets can already be reached in the 2021 – 2023 time frame⁵. As a first step, 48V Hybrids will enable “Electrification for the masses”.

Consequently, forecasts show a strongly increasing need for locally zero-emission vehicles (xEV)⁶, namely Plug-In Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV)

High-Voltage (HV) Li Ion batteries will be used for xEV powertrains in the years to come⁷. To enable sufficient electric driving ranges, chemistries leading to high volumetric energy density are employed. These cells need an environment that protects them from high / low temperatures and from contamination by particles or liquids, ensuring the required lifetime and preventing malfunctions.

2. Problem description

It is not possible to seal the battery system housing hermetically for total protection, as this would lead to mechanical stresses on the housing caused by pressure differences between environment and the HV battery system interior. If these exceed a maximum value depending on the battery system design (e.g. thickness of the housing's walls, required sealing forces), the resulting forces will lead to plastic deformation or even breaking of housing parts. Reduced compression of sealings can also result in leakages. To avoid this, pressure balancing is required.

The pressure balancing device has to efficiently hold back liquids and particles and let gas pass. Established solutions for this are e.g. vents and units with semi-permeable membranes. As gas enters the battery system interior, humidity can also enter. If the surface temperature of e.g. cooling plates falls below the dew point, condensation on those cold surfaces inside the system will occur. So an additional device is required to prevent condensation.

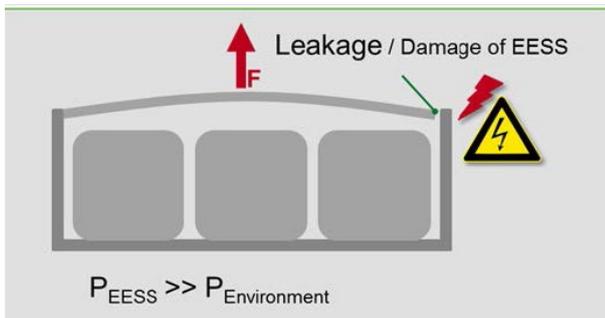


Figure 1: Battery System without pressure balancing



Figure 2: Battery System with pressure balancing

3. Humidity control

3.1 Protection against liquid water

3.1.1 Concept

To reduce the system complexity, two important functions – pressure balancing and emergency degassing – are combined into one unit. The unit has to ensure that no liquid water can enter the battery housing under all conditions.

3.1.2 Material selection

A PTFE membrane was validated for this application. The material is very durable, enabling lifetime applications.

As the fluorinated membrane’s low surface energy leads to repulsion of particles and liquids, the risk of clogging is minimized as long as the part is mounted in such a way that the membrane is oriented vertically or facing downwards. Another benefit is the independence of material properties to temperature changes, which also enables to use of the membrane in a degassing device.

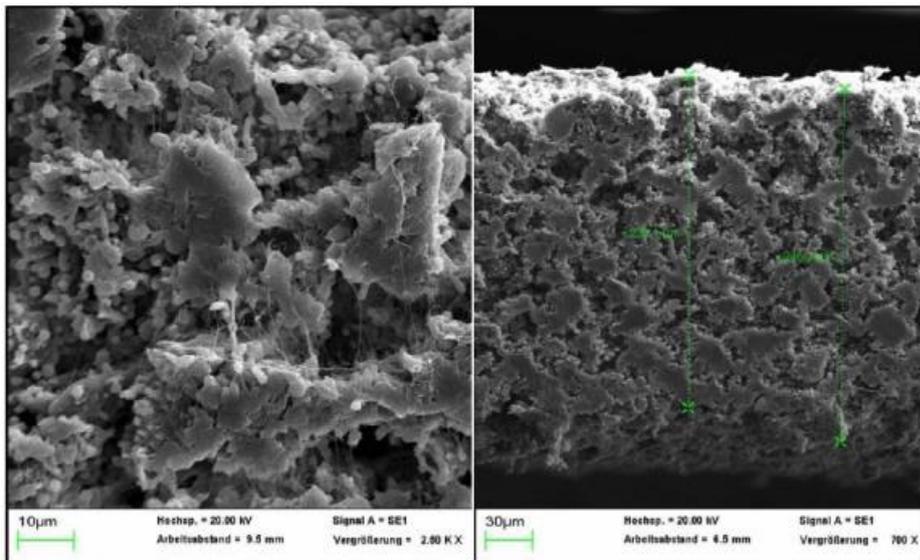


Figure 3: SEM picture PTFE membrane

3.1.3 Product design

The pressure balancing unit has to be designed in a way that allows the necessary air exchange and ensures that the required protection class is reached, e.g. according to ISO 20653. Pressure differences between the environment and the battery system interior can result from differences in air temperature and change in altitude during driving or air transport. While the gas exchange is enabled for pressure balancing, the battery system has to be protected from contamination from solids, e.g. dust, particles, liquids / water, and direct contact of the battery cell, e.g. by wire, also after a thermal incident. Water ingress during driving can happen through splash water or wading while passing a brook. Further risks are flooding events and steam-jet cleaning of the HV battery system.

The required membrane area can be calculated based on

- » membrane permeability
- » maximum allowed pressure difference between environment and HV battery system
- » free air volume inside the battery system
- » maximum expected changes in altitude during driving and transport
- » maximum expected temperature differences

To calculate the required membrane area for pressure balancing, the maximum pressure change the system can be submitted to must be calculated.

At a given time, the battery system contains a mass of air m , depending on

- » the free volume V inside the battery,
- » the temperature T , and
- » the pressure p .

This can be calculated using the known density of air ρ :

$$\rho(p, T) = \rho_n \cdot \left(\frac{p}{p_n} \right) \cdot \left(\frac{T_n}{T} \right) \quad (1)$$

where ρ_n , p_n and T_n are the reference values (1.18kg/m³, 288.15K = 15°C, and 1013mbar, respectively). The air mass m is calculated with formula (2):

$$m = V \cdot \rho(p, T) \quad (2)$$

In a closed system the air mass inside is constant, so any rise in T must be balanced by a rise in p in order to keep the density constant. As the housing can only withstand a maximum force resulting from the differential pressure Δp to the outside, the semi-permeable membrane of the degassing unit enables the flow of air mass in and out of the battery housing. Likewise, when the ambient (outside) pressure changes, the resulting Δp will have to be limited by allowing gas exchange via the membrane.

The amount of gas exchange via the membrane is proportional to the permeability P of the membrane, the membrane area A , and the driving pressure difference, Δp

$$\left(\frac{dm}{dt} \right) = P \cdot A \cdot \Delta p \quad (3)$$

The permeability is characteristic for the chosen membrane material, the maximum Δp together with the rate of pressure change, is usually customer-specific, as a result of temperature and/or altitude changes. Examples:

- » from -20°C to 65°C in 60 minutes,
- » hill climbing from 0m altitude to 2.500m altitude in 45min, or
- » air transport, from 0m altitude to 10.000m altitude in 15min

Often the air transport poses the greatest challenge.

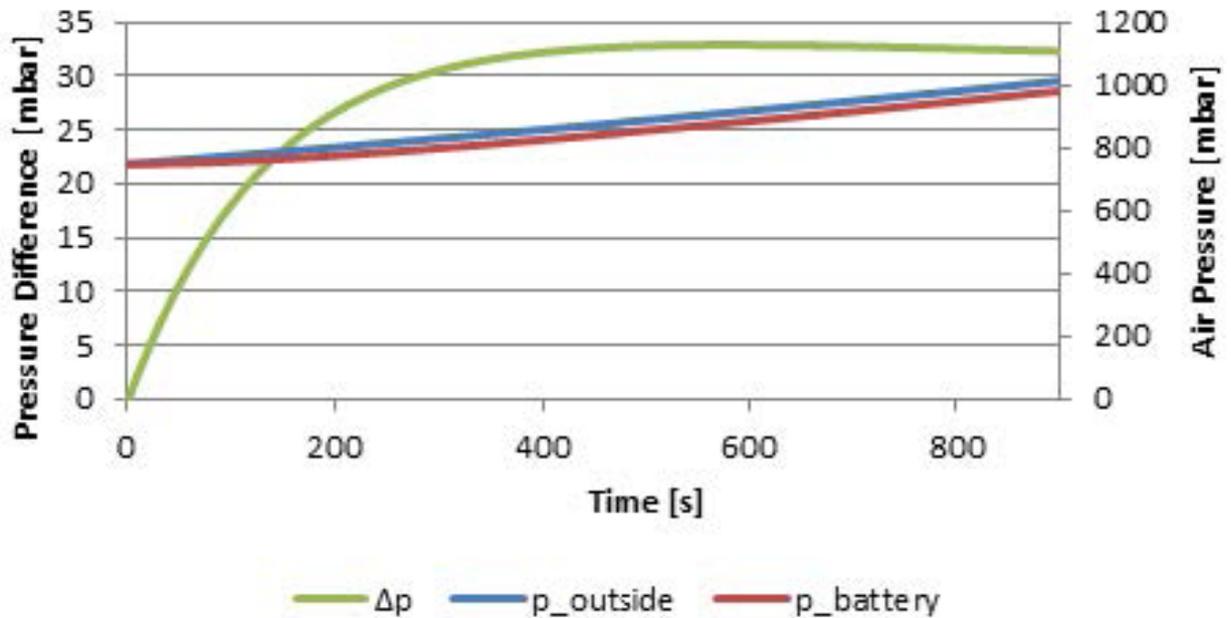


Figure 4: Calculated pressure changes caused by air transport

These requirements translate to an either positive or negative rate of change of the differential pressure ($d\Delta p/dt$) to the outside. The partial differential equation for Δp (4) can be integrated in time to yield the required membrane area A .

$$\Delta p(t) = \Delta p(t - \Delta t) + \frac{1}{\rho \cdot A} \cdot \frac{dm}{dt} \cdot \Delta t + \frac{d\Delta p}{dt} \cdot \Delta t \quad (4)$$

To avoid any damage to the battery system housing and seals, the membrane area has to be large enough to ensure that $\Delta p(t) < \Delta p_{max}$ as specified by the customer or battery manufacturer at all times.

The membrane's water repellence in combination with sealing concept, protection cap and supporting grid prevent water ingress even under challenging head-on steam-jet cleaning, reaching protection class IP6K9K, according to ISO 20653. A further point to consider is a potential reduction of the effective permeability of the membrane during lifetime.



Figure 5: Simulating thermal runaway of Li Ion battery cells

3.1.3.2 Emergency Degassing

The HV battery system consists of a large number of battery cells. In the case of overheating of a battery cell, a thermal runaway reaction can occur.

Possible reasons are short-circuiting caused by a damaged battery separator, severe overcharging, and evaporation / breakdown of the electrolyte⁹. The evaporated electrolyte can catch fire, leading to violent chemical reactions releasing large amounts of extremely hot gas in a very short time. The trigger point for this thermal runaway depends on the Li Ion chemistry used. The dilemma: the cells which are safest, i.e. show the highest trigger temperature have the lowest energy capacity. The chemistries favored in passenger cars are the ones which lower trigger temperatures⁹. So to prevent thermal runaways from happening, an efficient thermal management is required. The amount of gas released during thermal runaway strongly depends on chemistry used, cell size and the cell's state of charge^{10,11}. Comparative results show that up to 70-100 norm liters (i.e. at standard temperature and pressure) can be released from one xEV cell.

Considering that the temperature at which the gas is released is much higher (several 100 °C), the gas volume can reach 200 - 300 liters per cell. Considering a typical free air volume inside the battery system of 50 liters, even degassing of one cell will lead to high overpressure inside the system. The situation can become even more critical if the damaged battery cell initiates thermal runaway in adjacent battery cells, multiplying the negative effect. In order to prevent this, the housing must provide a degassing function which opens quickly to avoid massive pressure build-up and enables fast pressure relief through a sufficiently large open area to the outside. One possible solution is the classic pressure relieve valve. It is advantageous to integrate this function into the pressure balancing unit.

The membrane will be bulged towards a contact pin during gas formation. It will contact the base plate of the unit in the course of its outward deformation. A sharp pin on the inside of the base plate will cause the membrane to rupture at a specified overpressure, immediately opening the whole area for free flow from the battery housing to the outside, and therefore limiting the overpressure in the housing during the thermal runaway of one single cell to a safe value.

		HEV		PHEV		EV	
		min	max	min	max	min	max
Temperature	°C	400	500	400	700	400	800
Amount of gas	mol	0.5	1	0.5	3	3	4
Gas rate	mol / s	0.1	0.6	0.3	3	0.3	3
Amount of gas	L _{SATP}	12	24	12	73	73	98
Gasrate	L _{SATP} / s	2	15	7	73	7	73

Table 1: Results from thermal runaway testing of Li Ion battery cells^{10,11}



Figure 6: Pressure balancing unit with degassing function

The membrane’s almost temperature-independent mechanical properties enable pressure relief over a broad range of ambient temperatures.

To calculate the required membrane area for degassing, the following information is required:

- » gas volume released per battery cell
- » speed of gas release
- » size of the battery cell’s pressure vent
- » temperature of gas released

A partial differential equation for the pressure difference to the outside similar to the formula (4) can be used to calculate the necessary membrane surface. Before the membrane burst pressure is reached, the pressure is assumed to rise linearly. Once the membrane ruptures, the pressure increase from the released hot gas is counteracted by the pressure drop from the flow to the outside, quickly leading to an equilibrium near the maximum pressure, until after e.g. 3s no new hot gas is produced and the curve will exponentially fall towards the initial pressure. The maximum pressure reached in the event depends strongly on the free area of the opening which is fixed by the design, but only very weakly on the exact pressure at which the membrane ruptures. This brings benefits for the selected design.

In the end, the larger of the two areas from the two calculated scenarios – pressure balance and pressure relief - is chosen as the minimal required membrane area. Other scenarios are possible, e.g. calculating the required area for the emergency degassing which is independent of the membrane material, and then choosing a membrane with a permeability fitting to that area for the air exchange requirements.

3.1.3.3 Additional safety features

To protect the battery system from water entry during wading or flooding, a stabilization grid helps to limit the inward deformation of the membrane caused by external water pressure, thus stabilizing the membrane. To protect the system during steam-jet cleaning, a protection cap with an internal labyrinth structure is used which guides the water away from the membrane. This cap also prevents direct contact, e.g. by wire. Using a metal grid in combination with metal inserts and screws ensures contact protection even after fire.

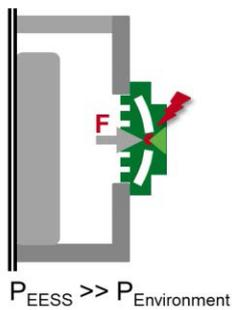


Figure 7: Mechanism of degassing function

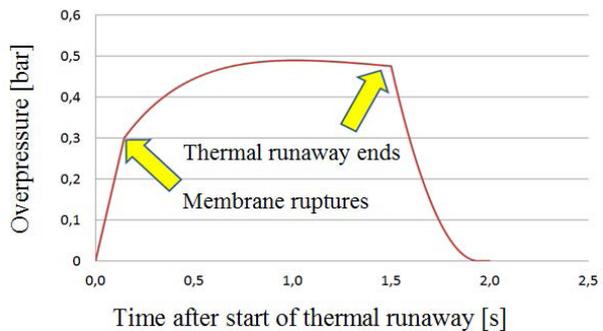


Figure 8: Pressure relief in case of degassing

3.2 Protection against water condensation

3.2.1 Concept

In addition, condensation of water on cold surfaces inside the HV battery system must be prevented to lower the risk of corrosion and electric shorts. The Mollier Diagram is used to visualize the relationship between relative humidity, absolute humidity, temperature and dew point. To avoid water condensation the absolute humidity inside the system must be kept at a level which will prevent the crossing of the dew point curve at the lowest temperature inside the battery system. At the dew point, the air is saturated with water, the curve showing a relative humidity of 100% is the dew point curve. If the temperature is lowered beyond the dew point at constant absolute humidity, water condensation occurs.

Consequently, to avoid water condensation the absolute humidity inside the system must be kept at a level which would not lead to crossing the dew point curve at the lowest temperature inside the battery system.

The risk of water condensation is especially high if liquid cooling with low coolant temperature is used for highly-efficient battery cell cooling during (fast-) charging and (fast) driving.

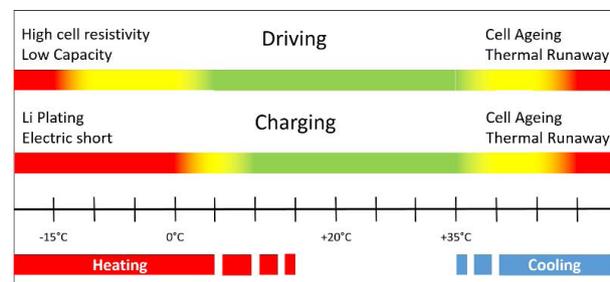
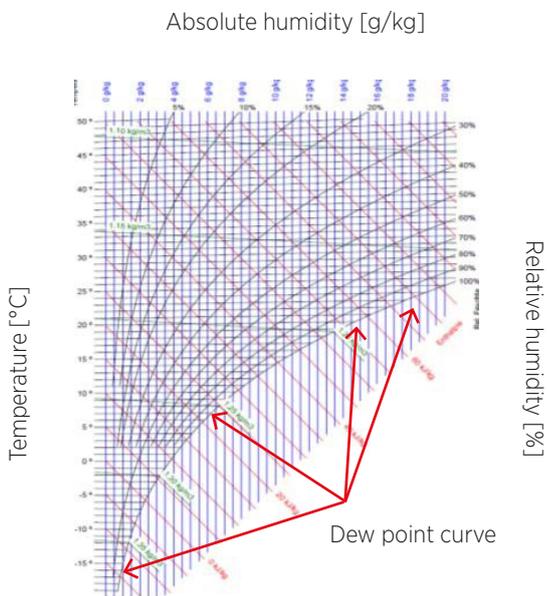


Figure 9: Mollier diagram (illustrative)¹²

Figure 10: Need for cell cooling

3.2.2 Material selection

Favorable materials for water vapor removal are adsorbents. Silica gel and zeolites can be used. Silica gel can bring benefits in cost and performance, binding up to 40 weight-% of water. Desorption can also be realized at much lower temperatures compared to zeolites. Desorption also takes place if air with very low absolute humidity enters the system. Adsorption of water leads to a reduction of absolute humidity inside the system, thus lowering the dew point (“dew point depression”). As an example, the figure below shows how adsorption of 50% of an absolute humidity of 20g/kg leads to a dew point depression from 25°C to 14°C.

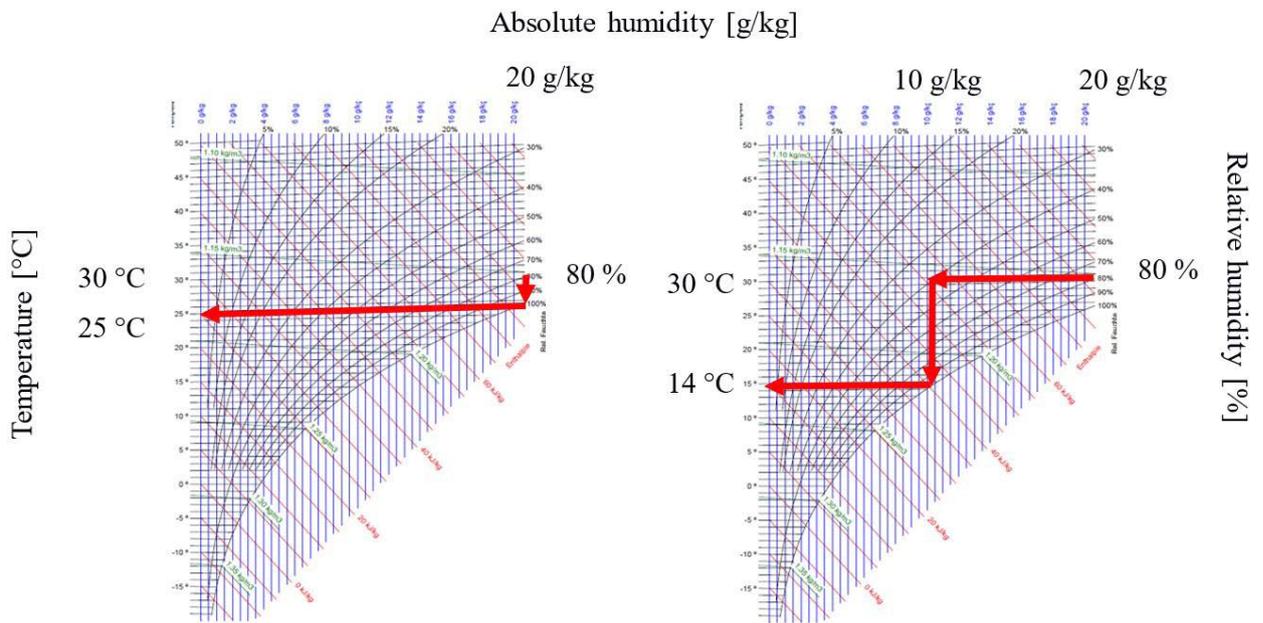


Figure 11: Dew point depression through adsorption (illustrative)

3.2.3 Product design

To calculate the required amount of adsorbent, the environmental conditions the HV battery system is exposed to must be known. Operation in hot, humid climates will pose the greatest challenge as the air entering the HV battery system will carry more water vapor, thus increasing the absolute humidity inside the system.

As efficient battery cooling is also required especially under these conditions, the risk of water condensation is especially high. With battery operating temperature T_{op} and the typical ambient temperature T_{am} and the free air volume in the battery housing V_{batt} , the volume of air V_{in} flowing into the battery is

$$V_{in} = 0,5 \cdot V_{batt} \cdot (T_{op} - T_{am}) / (T_{op} + T_{am}) \quad V_{in} = 0,5 \cdot V_{batt} \cdot (T_{op} - T_{am}) / (T_{op} + T_{am}) \quad (5)$$

The amount of water vapor m_{water} entering with the air is

$$m_{water} = V_{in} \cdot \eta(T_{am}) \quad (6)$$

$\eta(T_{am})$ is the amount of water vapor per m^3 at temperature T_{am} when saturated.

T_{am} strongly depends on the local climate where the car is operated. Using a value for T_{am} where vapor inflow is at a maximum results in a maximum water mass to be adsorbed, thus defining the required amount of adsorbent. In addition, the load-dependent water capacity has to be considered. The achievable dew point depression decreases with increased loading.

After the full adsorption capacity is reached, the part has to be replaced. As the adsorbent will capture moisture, the product is sealed inside the package to maintain the full capacity prior to assembly.

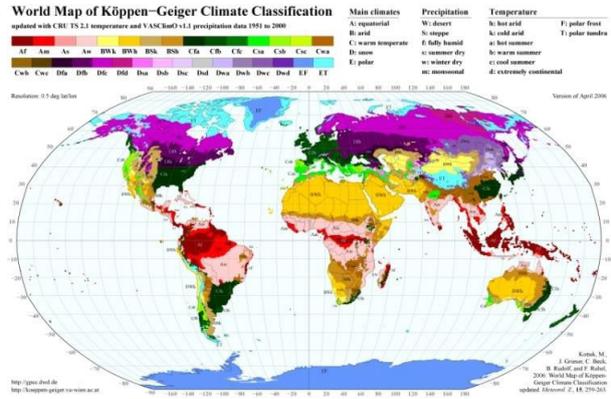


Figure 12: Köppen-Geiger Map¹³

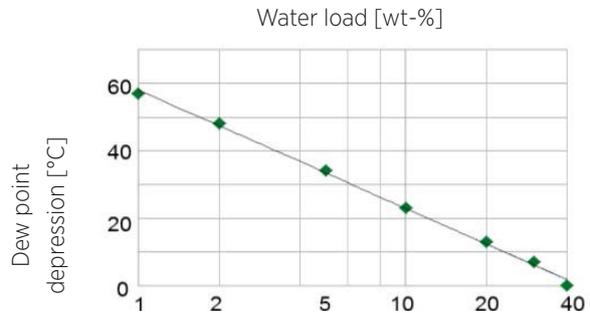


Figure 13: Dew point depression as function of water load



Figure 14: Air Dryer Cartridge.

References

- 1 UNFCCC, *Paris Agreement (2015)*, http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf, accessed on 2017-06-19
- 2 UNFCCC, *Paris Declaration on Electro-Mobility and Climate Change & Call to Action (2015)*, <http://newsroom.unfccc.int/media/521376/paris-electro-mobility-declaration.pdf>, accessed on 2017-06-19
- 3 Roland Berger – Automotive Competence Center, Forschungsgesellschaft Kraftfahrwesen mbH Aachen, *E-mobility Index Q2 2017 (2017)*, accessed on 2017-06-19
- 4 Nykvist, B., Nilsson, M., *Rapidly falling cost of battery packs for electric vehicles*, *Nature Climate Change*, ISSN 1758-678X, 5(2015), 329–332, <http://dx.doi.org/10.1038/NCLIMATE2564>
- 5 Manager Magazin online, Interview with Thomas Sedran, 21.10.2016, <http://www.manager-magazin.de/unternehmen/autoindustrie/interview-volkswagen-konzernstrategie-sedran-zu-elektroauto-offensive-a-1117222.html>, accessed on 2017-06-19
- 6 Bloomberg New Energy Finance, *Electric vehicles to be 35% of global new car sales by 2040 (2016)*, <https://about.bnef.com/press-releases/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040>, accessed on 2017-06-19
- 7 Thielmann, A., Sauer, A., Wietschel, M., *Gesamt-Roadmap Lithium-Ionen-Batterien 2030 (2015)* <http://www.isi.fraunhofer.de/isi-wAssets/docs/t/de/publikationen/GRM-LIB.pdf>, accessed on 2017-06-19
- 8 Bruning, A., *Why Li-ion batteries catch fire*, *Chemical & Engineering News*, ISSN 1520-605X, 92(2016), 33, <http://cen.acs.org/articles/94/i45/Periodic-graphics-Li-ion-batteries.html>, accessed on 2017-06-19
- 9 Reid, G., Julve, J., *Second Life-Batteries as flexible storage for renewable energies*, 2016, http://www.bee-ev.de/fileadmin/Publikationen/Studien/201604_Second_Life-Batterien_als_flexible_Speicher.pdf, accessed on 2017-06-19
- 10 Golubkov, A.W., Fuchs, D., Wagner, J., Wiltzsche, H., Stangl, D., Fauler, G., Voitic, G., Thaler, A., Hacker, V., *Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes*, *RSC Advances*, ISSN 2046-2069, 4(2014), 3633-3642
- 11 Golubkov, A.W., Scheikl, S., Planteu, R., Voitic, G., Wiltzsche, H., Stangl, C., Fauler, G., Thaler, A., Hacker, V., *Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge*, *RSC Advances*, ISSN 2046-2069, 5(2015), 57171-57186
- 12 Available e.g. from http://www.dolder-ing.ch/wissen/Lueftung-Klima/h-x-diagramm/Mollier_h-x-diagramm_Bild.htm
- 13 Available e.g. from <http://koeppen-geiger.vu-wien.ac.at/>

Authors

Dr. Michael Harenbrock finished his Ph.D. thesis on Organic Chemistry in 1994. After joining MANN+HUMMEL GMBH in 1998, he managed the Materials Development Department for filters. Since 2013, he is responsible for company´s strategy towards Electric Mobility and Fuel Cells. He represents MANN+HUMMEL in several clusters and industry organizations. His current position is Business Development Manager E-Mobility.
Corresponding author: MANN+HUMMEL GMBH, Schwieberdinger Str. 126,71636 Ludwigsburg, Germany, michael.harenbrock@mann-hummel.com

Dr. Stefan Kunze studied physics in Tübingen and Toronto. He finished his Ph.D. thesis on astrophysical applications of numerical methods in 2000. After joining MANN+HUMMEL in 2008, he was working as a CFD Engineer in the thermodynamics group in Advanced Engineering. His current position is Simulation Expert CFD and FEA, and Expert Algorithms for IoT in advanced development.

Stephan Niemeyer studied Process Engineering at the Hochschule Mannheim. He has been working with MANN+HUMMEL since 1999 as a development engineer responsible for development and testing of adsorptive air dryers for pneumatic systems on commercial vehicle applications and battery housings.