INVESTIGATION OF PROTECTIVE NANO-BASED SURFACE COATINGS FOR DRY HYBRID COOLERS

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Abstract: Efficient rejection of waste heat is essential especially for thermally driven chillers, to keep up cooling capacity at demanding summer operation conditions. A suitable alternative to large surface reserves of dry coolers is to boost their performance by temporary wet mode operation by spraying water on the heat exchanger. But due to corrosion and fouling problems this is usually limited to a few hours. One approach to avoid this is to protect the dry coolers with special surface coatings. This paper presents the results of various experimental investigations of dry coolers equipped with hydrophilic and hydrophobic coatings. Long-term intermittent spray operation of small test coolers with tap water was performed in a laboratory test rig. The microscopic examinations and contact angle measurements showed that even best hydrophobic surface was rapidly turning to hydrophilic. Nevertheless, at over 600 hours of intermittent spray and dry operation some coatings showed positive results - a reliable corrosion protection and the positive effect of additional evaporative cooling with a minimum of water could be proved.

Key Words: hybrid cooler, hydrophilic and hydrophobic surface coatings, absorption cooling

1 INTRODUCTION

Efficient rejection of waste heat is essential especially for thermally driven chillers, to keep up cooling capacity at demanding summer operation conditions. Today either dry coolers or wet tower coolers are used. The advantages of a dry cooler are the lower operating and maintenance costs compared to wet cooling towers. But during peak loads at high ambient temperatures in summer the cooling water temperature is unfavourably rising and thus the chiller efficiency decreases. Large absorption chillers traditionally operate with wet cooling towers. However wet cooling towers consume always water and require a water treatment system to avoid biological fouling, hygienic problems or operational outage.

Hybrid dry coolers, which represent a combination of air cooled dry coolers and closed circuit wet cooling towers, offer a good alternative. A hybrid dry cooler could operate in dry mode most of the time, when the ambient air temperature is low enough to allow sufficient cooling water temperature and heat rejection capacity. If the ambient temperature increases and the required process temperature can not be covered any longer, the heat exchange surface of

the hybrid cooler is sprayed with water. The water evaporates on the finned or lamellas surface and brings an additional cooling effect, thus enhancing the cooling capacity and reducing the chiller condenser temperature. In this operation mode, the cooling effect is not only based on sensitive heat, but also on the latent heat of evaporation. The hybrid dry cooler is then performing like a wet cooling tower, which enables its use as a heat rejection device for small to medium range ab- and adsorption chillers.

But from the sprayed water, which is evaporating on the heat exchanger surface, usual water ingredients such as mineral salts or organic particles would remain on the surface and lead to fouling and finally blocking of the heat exchanger. For this reason the amount of sprayed water is normally significantly larger than the amount of water necessary for the cooling effect. The surplus water flushes the fouling off the surface of the heat exchanger. A recirculation of the surplus water is necessary to limit the water consumption. Nevertheless continuous evaporation of water causes a concentration of the mineral content, so that water analysing and treatment as well as periodic drainage lead to additional operating costs. Another possibility to avoid fouling is to use cleaned and demineralised water for spraying. But also in this case a water treatment unit is necessary.

A new approach to avoid fouling is to apply self cleaning coatings on the heat exchanger surface, so that dirt does not adhere. Such coatings have been investigated in the past for various applications, e.g. roof plates, building fabrics, textiles, glass, mirrors, PV-collectors etc. [Bahnemann 2005]. In general self cleaning coatings are divided into two categories: hydrophobic and hydrophilic [Parkin and Palgrave 2005]. Whether a surface is hydrophobic or hydrophilic can be evaluated by the angle formed by the edge of a water droplet with the surface. Surfaces with contact angles less than 90° are called hydrophilic (less than 10° super-hydrophilic) and surfaces with contact angles greater than 90° hydrophobic (greater than 150° super-hydrophobic) [Forbes 2009] [Patel et al. 2010].

1) Hydrophobic coatings: Modification of the surface in a way that water ingredients do not adhere on the heat exchanger surface. This modification can be realised by special hydrophobic coatings based on nanotechnology. Such a coating supplies the surface with a special microscopic structure, which makes the surface extremely hydrophobic. The super hydrophobic property prevents the surface from being wetted by water. The contact angle of water droplets on the coated surface is much larger than on a plain surface. The water droplets roll off and take contaminants and mud with them. This self cleaning effect is known as “lotus effect”.

2) Hydrophilic coatings: Modification of the surface with a special microscopic structure, which makes the surface extremely hydrophilic. The super hydrophilic property leads to very well wettable surfaces. The contact angle of water droplets on the coated surface is much lower than on the original surface. The aim is that the water can spread extremely well on the surface so that inorganic soil is subverted and be rinsed off. This self cleaning effect is known as “inverse lotus effect”.

This paper presents the results of various experimental investigations with such modified hybrid cooler under typical operating conditions. Main topics are the performance of coolers, the water consumption in wet operation mode, the resistance of the coatings in continuous operation and the resistance of the coated heat exchanger lamellas against corrosion.

The investigations presented in this paper were embedded in the research project “Development of a small scale thermally driven absorption chiller using membrane technology for air conditioning purposes in residential buildings” funded by the German Federal Ministry of Economics and Technology (BMWI) and supported by the Project Management Organization Jülich (PTJ).

2 METHODOLOGY AND EXPERIMENTAL SETUP

Within this study suitable coatings to protect the lamellas of dry coolers against corrosion and fouling have been identified and applied on small test coolers. Several custom-made heat exchangers as displayed in Figure 1 were sent to external service companies to be coated either hydrophobic or hydrophilic by different methods (plasma deposition, immersion baths, spraying). Long-term intermittent spray operation of the small test coolers with tap water were performed in a laboratory test rig. The main interests of the function and performance tests were the spray water consumption for different operation conditions, the functionality of the spray water system in view of the wetting grade of the heat exchanger and the influence of the coating on the heat transfer. Before and after the performance tests microscopic examinations as well as contact angle measurements were carried out for the test coolers. Finally the measurement data were analyse and assessed.

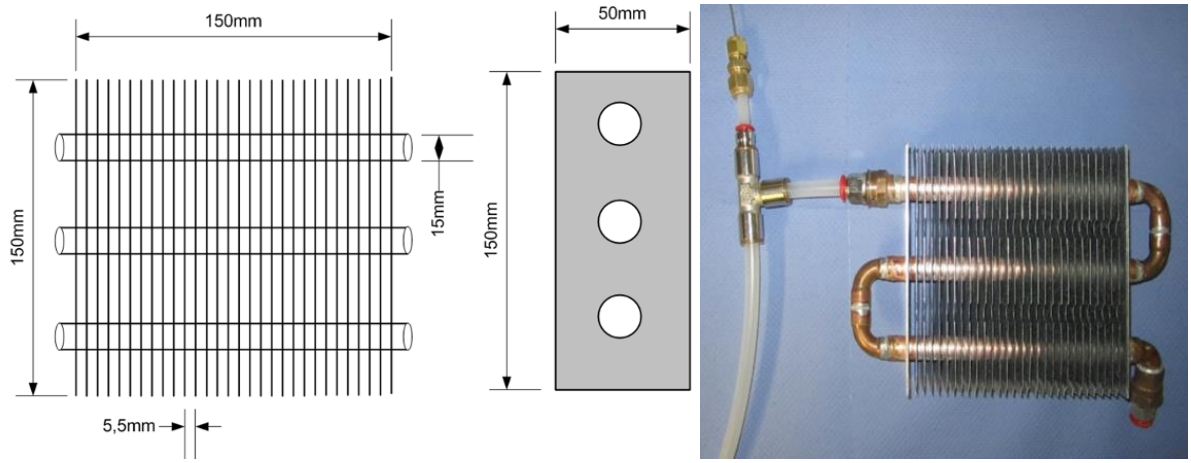


Figure 1: Aluminium finned air/water heat exchangers as test coolers for spray tests

Experimental testing was performed using a test chamber wind tunnel equipped with the heat exchangers including an untreated reference unit (see Figure 2). The heat exchangers are connected in parallel.

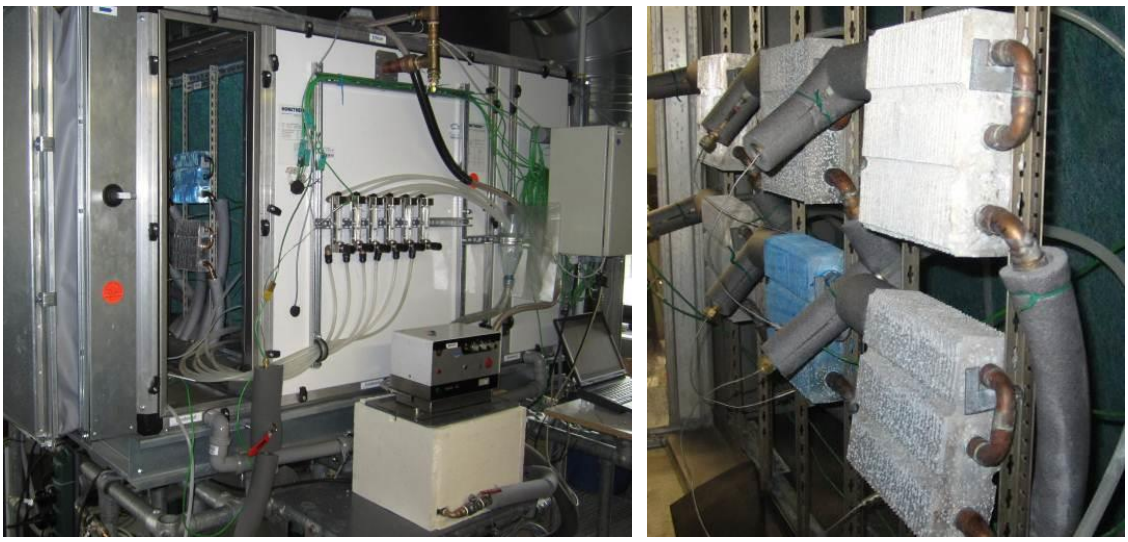


Figure 2: Test chamber for hybrid cooler performance and ageing testing with 6 test coolers installed

As displayed in the hydraulic and sensor diagram (Figure 3), the test rig includes a water circuit, equipped with an electrical heater and a circulation pump, which is used to supply warm feed water to the heat exchangers. The feed water flow is the same to all coolers. The temperature of the cooler outlet water of each unit can be measured separately. By this means the cooling load of each unit can be determined from water flow and temperature difference.

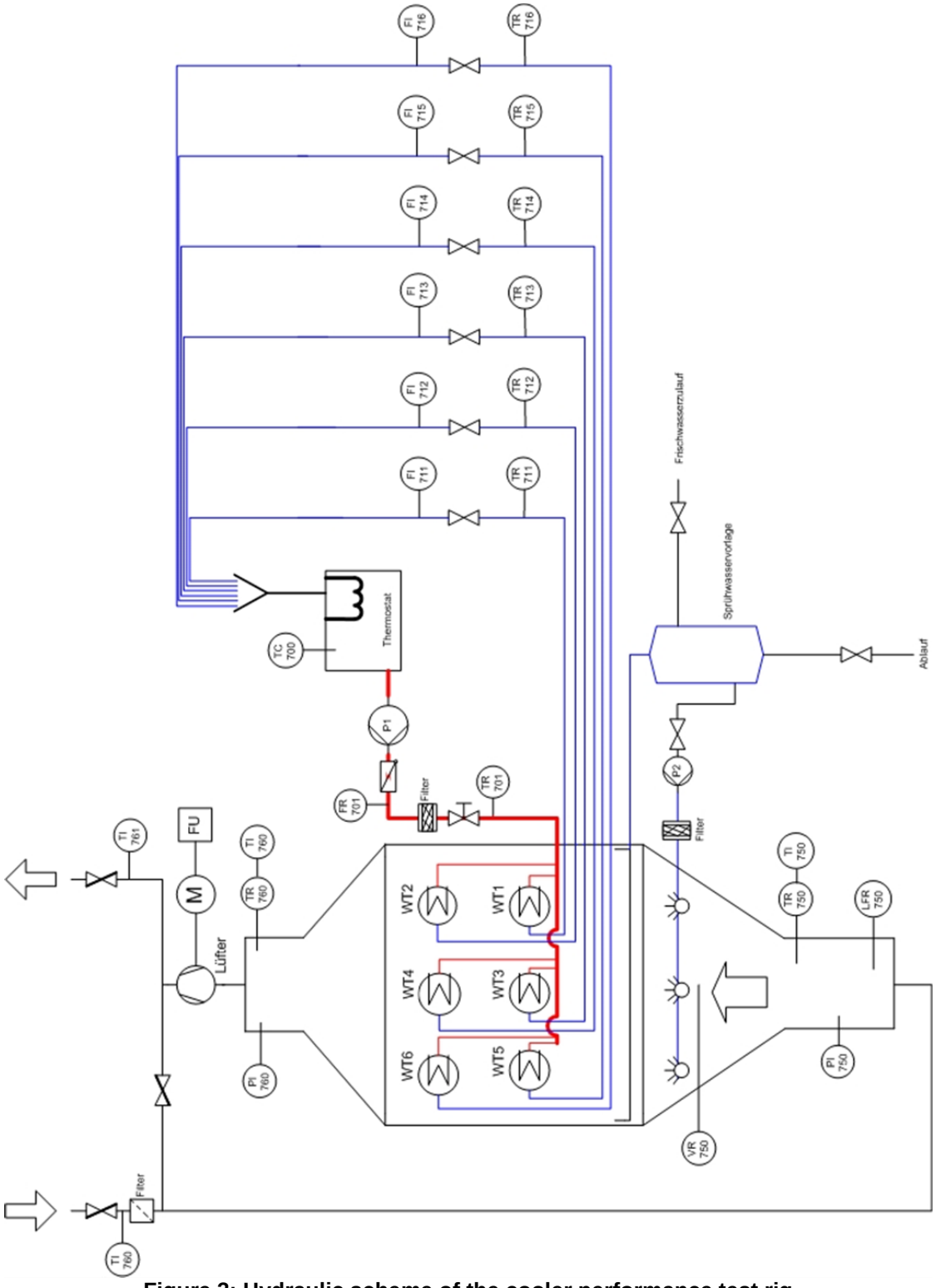


Figure 3: Hydraulic scheme of the cooler performance test rig

3 EXPERIMENTAL INVESTIGATIONS AND RESULTS

Within the experiments the coolers are operated in dry air flow, or wet by spraying water on them. A gear pump is supplying the spray water from a tank beneath the wind tunnel. The water is just filtered but not treated. To achieve similar conditions to all coolers, each has its own spray nozzle with the same characteristic. The water spray partly leads to adiabatic cooling of the air and touches the lamella surface where additional evaporative cooling takes place. Thus the performance of the coolers strongly increases with the water spray. The excess spray water is trapped in a demister mat behind the coolers and drains back to the tank. The evaporated water is automatically replaced by fresh tap water, an excess of fresh water limits the increase of the mineral content. The dry and wet operation periods for the hybrid mode are controlled by a process control and were varied during the experiments.

The air volume flow, respectively the velocity of the air passing the coolers, is adjusted by an inverter controlled axial fan. To keep the air humidity in a realistic range, mostly fresh air is drawn from outside and is mixed with some circulation air. Although the air temperature varies during the day and with the weather conditions, the operation conditions of the coolers have to be kept constant. This is achieved by controlling the supply temperature of the cooler cycle to keep a constant ΔT to the air flow. As the reference temperature the wet bulb temperature was chosen, which is determined by the process control from relative humidity and dry bulb temperature. By keeping the ΔT water/air at constant value (e.g. 10 K) and automatic variation of the dry/wet intervals, the performance tests were run completely automatically.

As an example Figure 4a shows the cooler performance increase from below 60 W in dry mode to 110 W after 30 s of water spray. In the 1 hour interval between the spray pulses the coolers were allowed to dry again, reaching the same level in dry mode as before. In Figure 4b a spray pulse of 30 s is followed by only 10 min drying, thus the coolers didn´t dry completely and the cooling load varies from about 80 to 115 W.

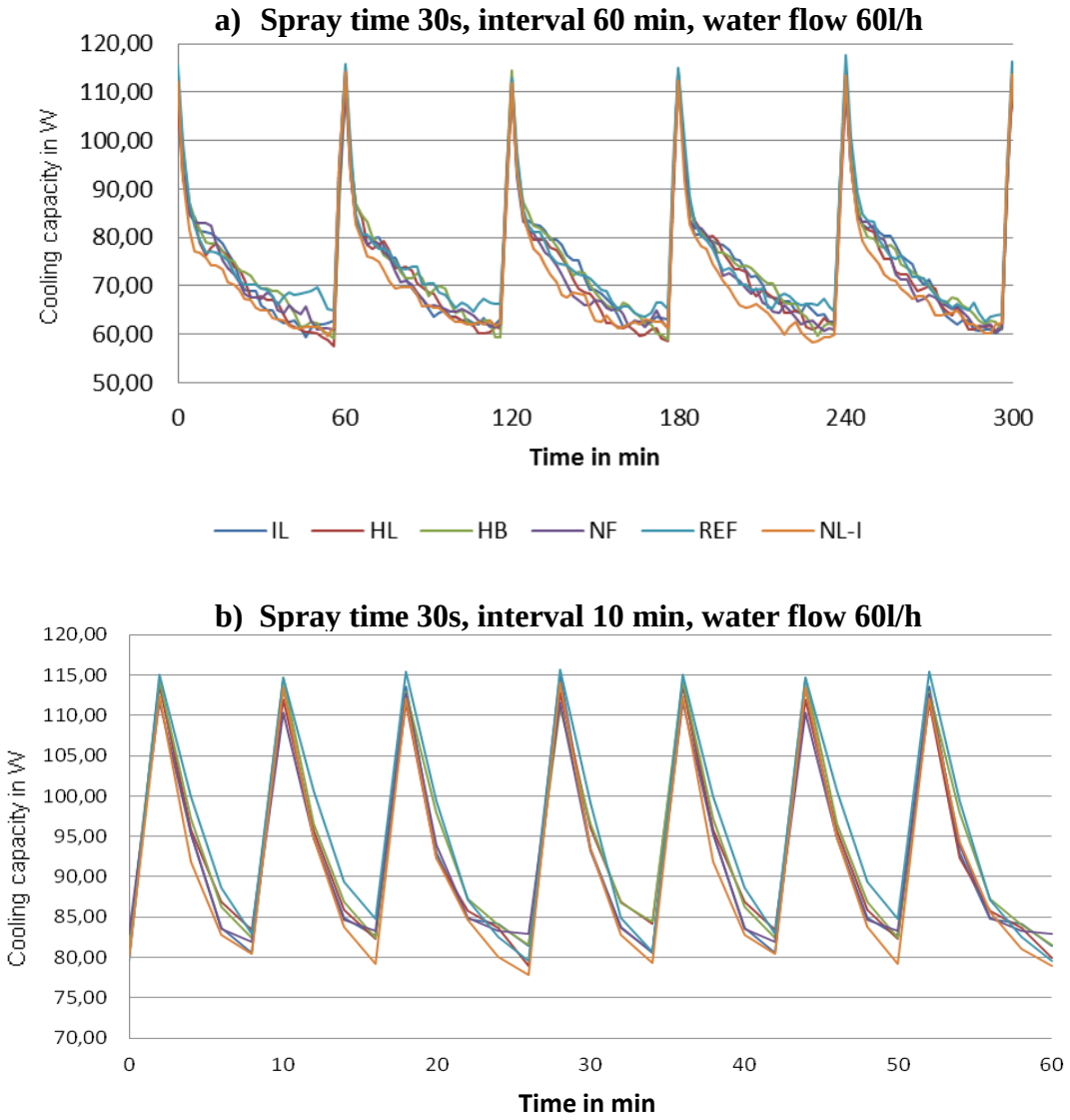


Figure 4: Cooler performance in automatic operation – different intervals

The complete set of control parameters which determines the variation of the dry/wet intervals over several days is summarized in Table 1. The interval time (start of spray n until spray n+1) is varied from 10 s to 300 s. The duration of a spray period is varied from 100% (of the interval length = permanent) down to 0% (= no spraying). Each of those parameters is kept constant for exactly one hour. So any 12 h cycle starts with permanent spraying and then the share of spray time is decreased until the channel is running dry for 1 hour.

Table 1: Parameters for hybrid cooler performance tests

		Interval (from spray pulse to next pulse)				
Interval [s]		10	30	60	120	300
Interval [min]		0,17	0,5	1	2	5
Number of int. [1/h]		360	120	60	30	12
Spray duration per interval		Spray time total [min/h]				
	100 %	60	60	60	60	60
	80 %	48	48	48	48	48
	60 %	36	36	36	36	36
	40 %	24	24	24	24	24
	30 %	18	18	18	18	18
	20 %	12	12	12	12	12
	15 %	9	9	9	9	9
	10 %	6	6	6	6	6
	5 %	3	3	3	3	3
	2 %	1,2	1,2	1,2	1,2	1,2
	1 %	0,6	0,6	0,6	0,6	0,6
	0 %	0	0	0	0	0

All relevant operation parameters (sensor data and calculated values) were displayed and recorded, as shown in Figure 5 for a complete set of cycles. The diagram clearly shows that the cooling performance at dry conditions was more than doubled by water spraying. The second of the 12 h spray cycles is displayed in more detail in Figure 6.

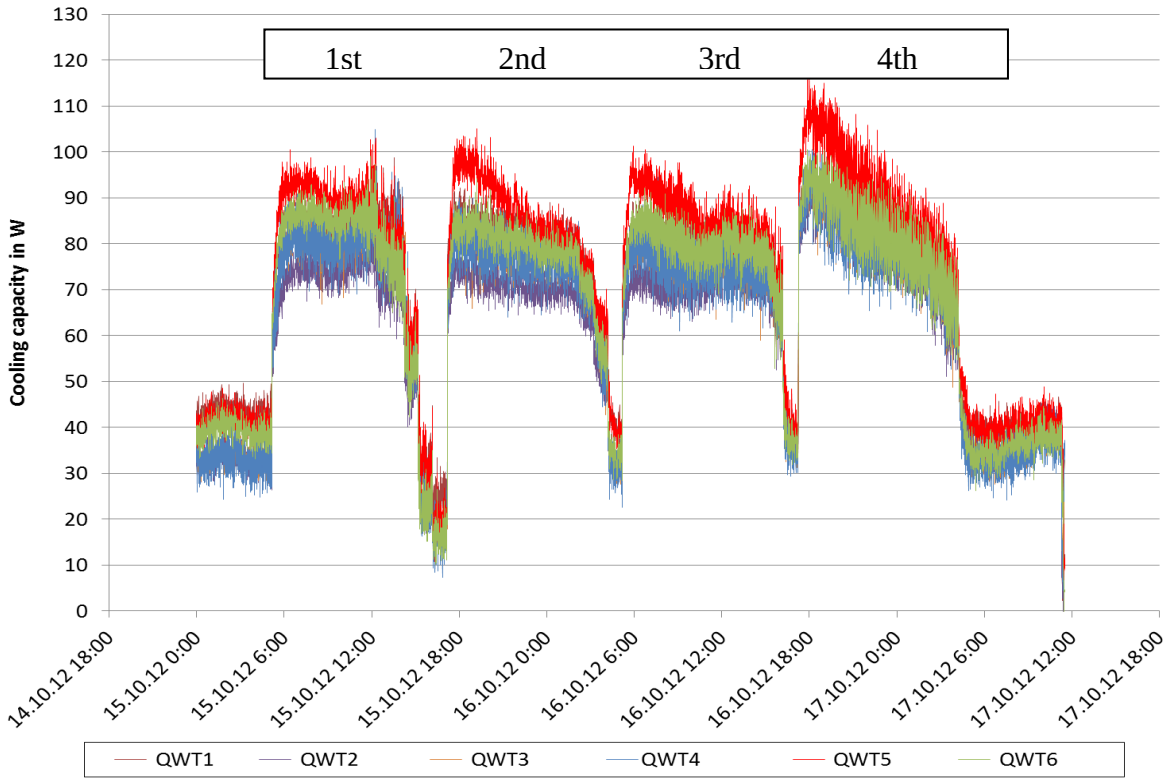


Figure 5: Hybrid cooler test cycle with spray/dry interval parameter variation (over 60 hrs)

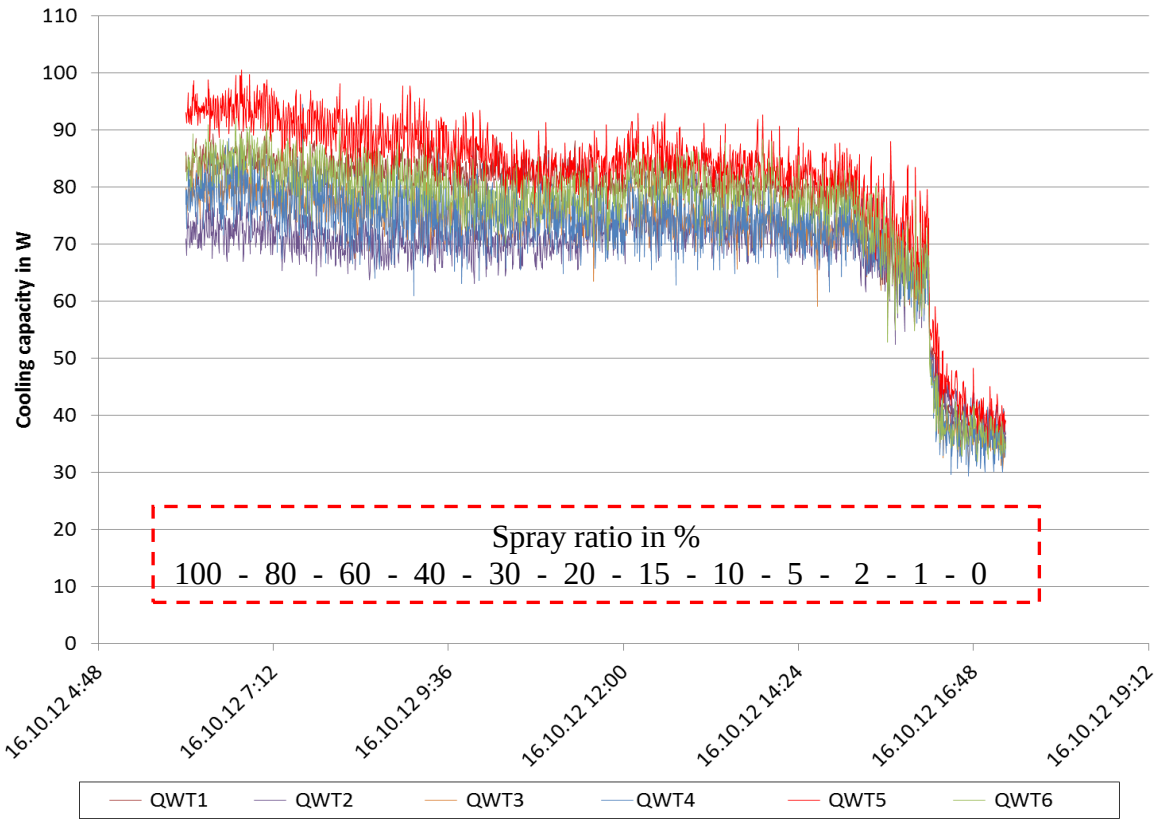


Figure 6: Hybrid cooler performance over 2 hrs periods with decreasing spray intensity

From the diagrams it can be read that with decreasing spray ration the cooling performance decreases only slightly until a ratio of below 5 to 2% is reached. Thus in hybrid coolers the spray water consumption could be reduced to at least 5 % of the usage at permanent spray and still be enough to ensure the desired power enhancement by evaporative cooling.

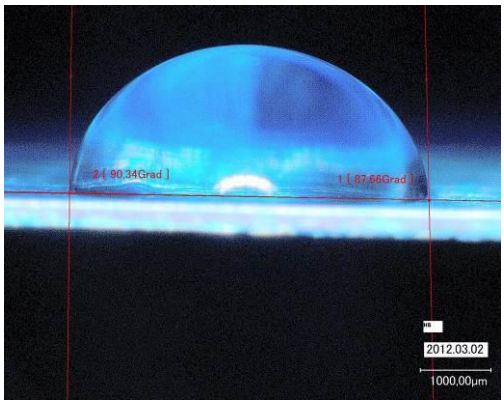
Taking into account that the calculated cooling loads are fluctuating due to small the ΔT in-out of the units and air flow turbulences a second finding from the performance test is, that the different coatings did not lead to very much differing cooling powers. The visible differences are mostly due to fluctuating variations of sensor readings, although the sensors were calibrated thoroughly several times and the heat balances set to zero at zero air flow.

Corrosion and surface protection

Following the performance tests microscopic examination as well as contact angle measurements were carried out. The main differences between the heat exchangers were found in the quality of the surface protection, respectively the corrosion during the long period of hybrid dry/wet operation with circulated tap water in the flow channel.

As mentioned before some of the externally applied coatings were supposed to be hydrophobic, some other hydrophilic. Before starting the spray tests the properties of the different coatings were checked by microscopic examinations (see Figure 7). It was found that the desired properties could not be confirmed in any case.

Nevertheless it was found during the spray tests that even best hydrophobic surface was quite rapidly turning to hydrophilic, as the contact angle measurements showed, see Table 2 and Figure 9. Where the coating did not give sufficient protection, e.g. at the problematic zones around the sharp edges of the metal fins, corrosion starts soon, as displayed in Figure 8.



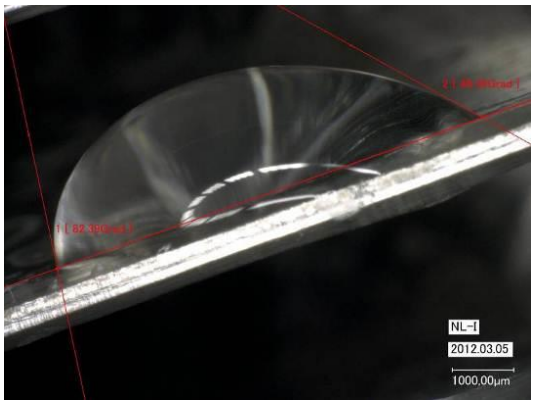
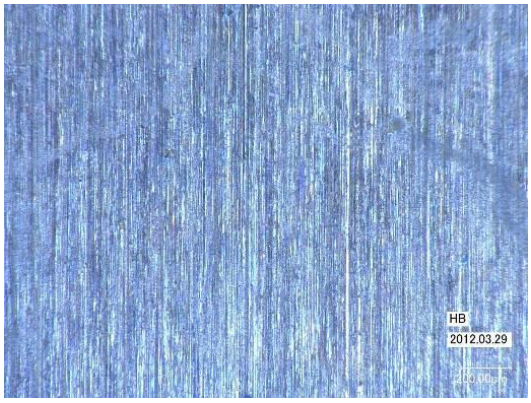


Figure 7: Initial contact angles of water on Alumina lamella a) hydrophobic surface b) hydrophilic surface



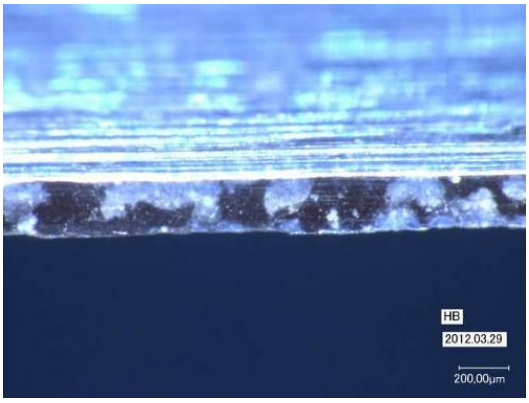


Figure 8: a) Surface of coated test heat exchanger before beginning of spray tests b) Corrosion on the front edge of a cooler lamella, after some weeks in the hybrid spray test chamber

Table 2: Change of contact angles during spray tests

			contact angle (static) [°]			
Kind of Treatment	**Scheduled Properties**	**Probe**	**initially**	**Mar. 12**	**May 12**	**Oct. 12**
Plasma	hydrophobic	NF	95	35	21	9
Immersion bath	hydrophilic	HL	75	30	30	-
Immersion bath	hydrophobic	HB	90	40	34	29
Immersion bath	hydrophilic	IL	75	25	22	8
Immersion bath	hydrophobic	NL-1	76	40	38	-
Immersion bath	hydrophobic	NX	-	-	90	20
Immersion bath	hydrophilic	NX+	-	-	50	20
-	-	REF	90	20	12	10

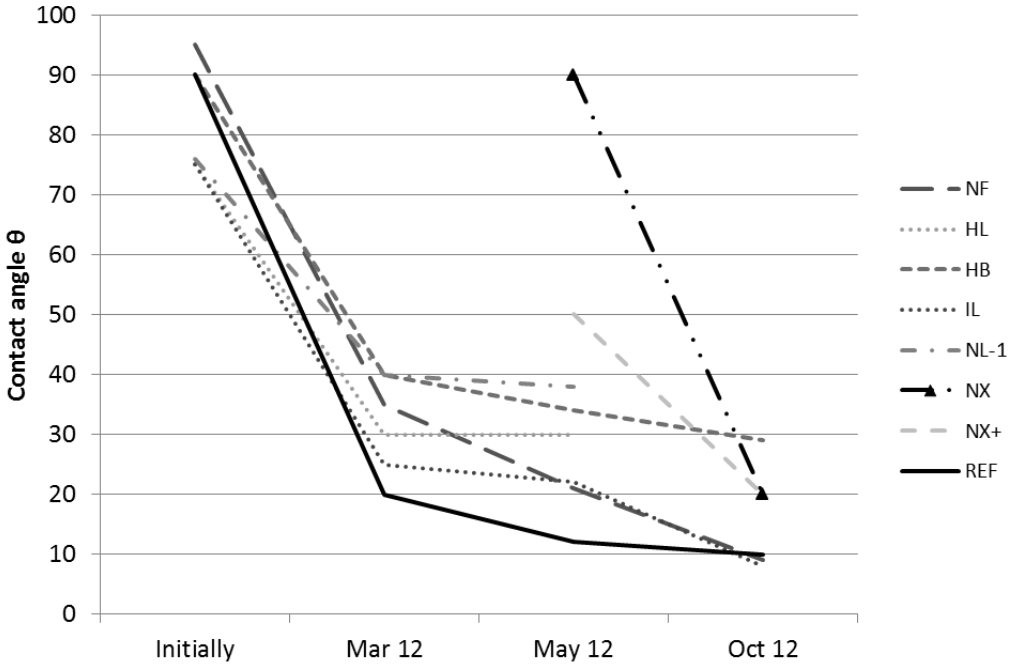
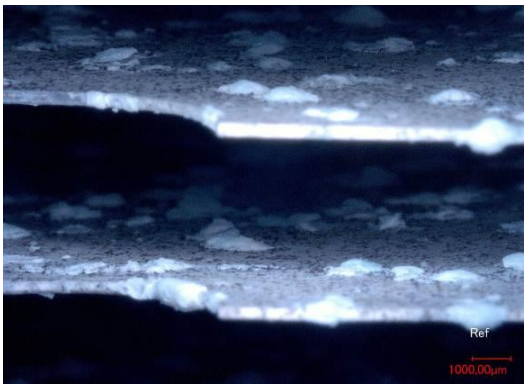


Figure 9: Change of contact angles during spray test

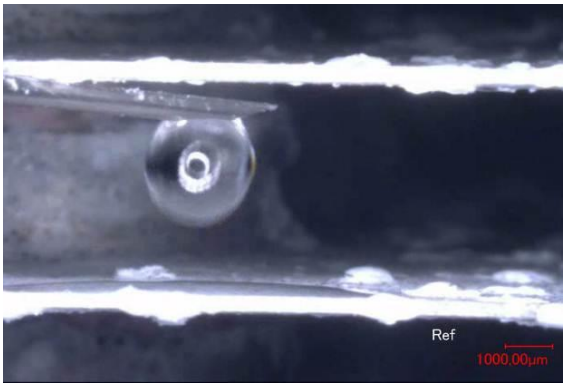
After about 600 h of intermittent dry/wet mode and periods without spraying, the various coolers showed clear differences concerning the corrosion rate, as displayed in Figure 10.

The uncoated reference probe showed the typical aluminium pit corrosion (Figure 10a) and a strongly hydrophilic surface due to the porous structure of the mineral and corrosion layers (Figure 10 b). The plasma coated Nanofinish probe in c) and d) showed the same effect, but with slightly reduced corrosion. The immersion coating NX (initially hydrophobic) just led to a thin layer of minerals and small pits, while the surface property turned hydrophilic.

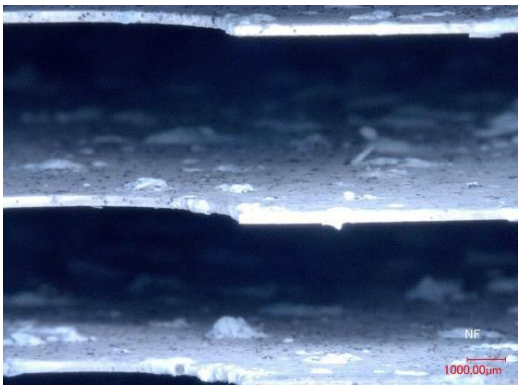
The best results were achieved with the immersion coating of NX and NX+, where apart from a very thin grey coloured layer no corrosion was visible, not even at the edges of the fins. The initially hydrophobic surface of NX turned to the opposite, like all other probes. The coating NX+ consists of two layers to make it hydrophilic. Since the hydrophobic surface became hydrophilic during operation, the additional “+” layer does not seem to be necessary.



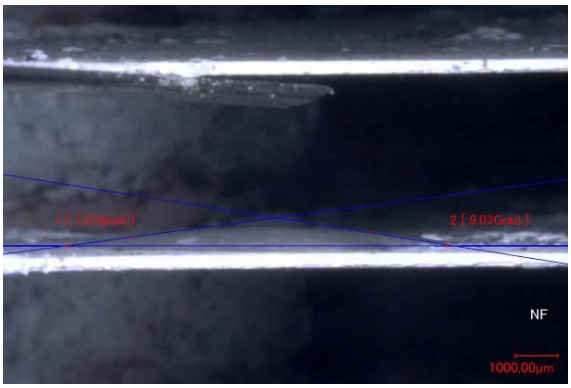
a) Reference probe, not coated – severe corrosion on lamella surface



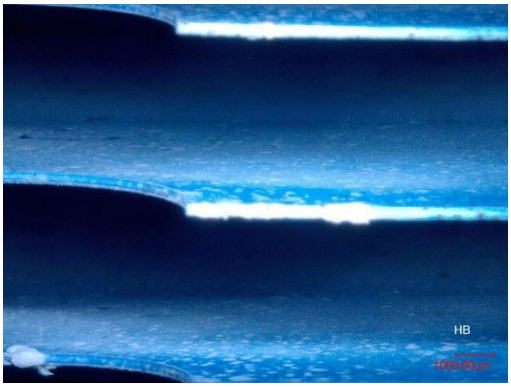
b) Reference probe turned hydrophilic, water droplet immediately spreads on surface



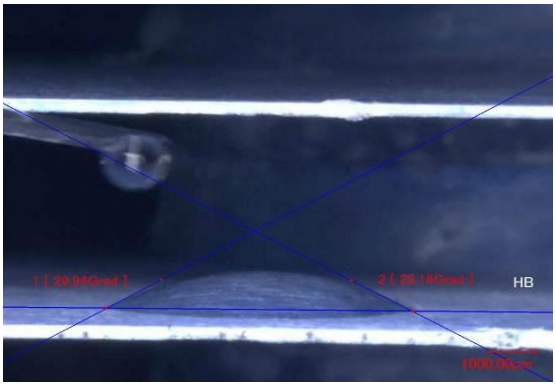
c) NF – corrosion on lamella surface



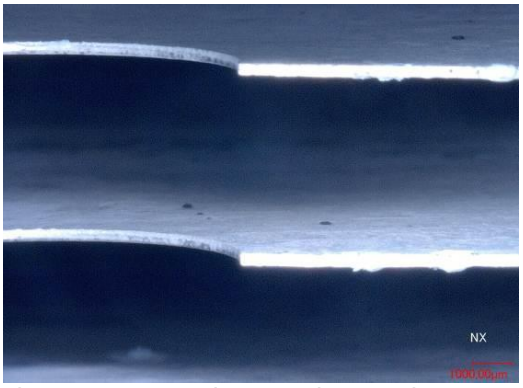
d) NF - strongly hydrophilic surface



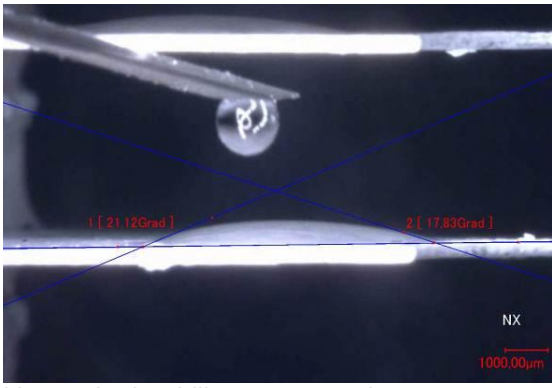
e) HB – mineral layer on lamella surface but almost no corrosion



f) HB – surface became hydrophilic



g) NX – no corrosion, good protection, very thin mineralic layer



h) NX - hydrophilic contact angle

Figure 10: Appearance of test cooler surfaces after about 600 h of hybrid spray test

4 CONCLUSIONS

The results of various experimental investigations of dry coolers equipped with hydrophilic and hydrophobic coatings were presented in this work. Long-term intermittent spray operation of small test coolers with tap water was performed in a laboratory test rig. The positive effect of additional evaporative cooling with a minimum of water could be proved. In wet cooling mode the cooling capacity of dry heat exchangers could be enhanced by a factor of 2. By controlled water spray in short intervals the water consumption was reduced down to 5 – 10 % without a significant loss in performance compared to constant spraying. Within the performance tests the cooling power of the differently coated heat exchangers did not differ significant. In periodic microscopic examinations and contact angle measurements of the test coolers an irresistible change to hydrophilic surfaces was observed in all cases. Nevertheless, at over 600 hours of intermittent spray and dry operation some coatings showed positive results - a reliable corrosion protection and the positive effect of additional evaporative cooling with a minimum of water could be proved.

Finally, it can be stated that special surface coatings for standard dry coolers to avoid fouling and corrosion in wet operation mode seem to be very promising. Nevertheless further R&D work including long term tests in real applications is required.

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