EnE-HVAC

Energy Efficient Heat Exchangers for HVAC Applications

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Contents

Objective

The objective of this part of work package 5 (WP5) is to demonstrate the technologies developed in work packages 1, 2 and 3 and validated in work package 4. This report describes the work that has been done since the last deliverable report in this WP *“D5.1: Design and production of demonstration plants”*.

Introduction

Three different demonstrations have been carried out at LU-VE, Exhausto and Danish Technological Institute.

LU-VE has demonstrated an anti-ice surface on a heat exchanger, and Exhausto has demonstrated an anti-ice surface-treated heat exchanger in an air-handling unit. At Danish Technological Institute, a nano-structured plate-shell heat exchanger from Vahterus has been demonstrated in a NH_3 setup.

All demonstrations have been performed in laboratories to ensure the best and most meaningful results for the project. It does not make sense to demonstrate anti-freezing surfaces from April to October, where there are no icing problems in air-handling units due to the warm ambient temperatures and the Vahterus heat exchanger was of too low capacity to be tested at the relevant end-users.

Demonstration of Anti-freezing surfaces at Exhausto

Introduction

The measuring shall prove if the developed coating has any impact on the icing up of the counter flow heat exchanger in VEX320C. The target for this coating is that it postpones the icing up of the counter flow heat exchanger, in order for the annual temperature efficiency to increase.

Measuring set-up

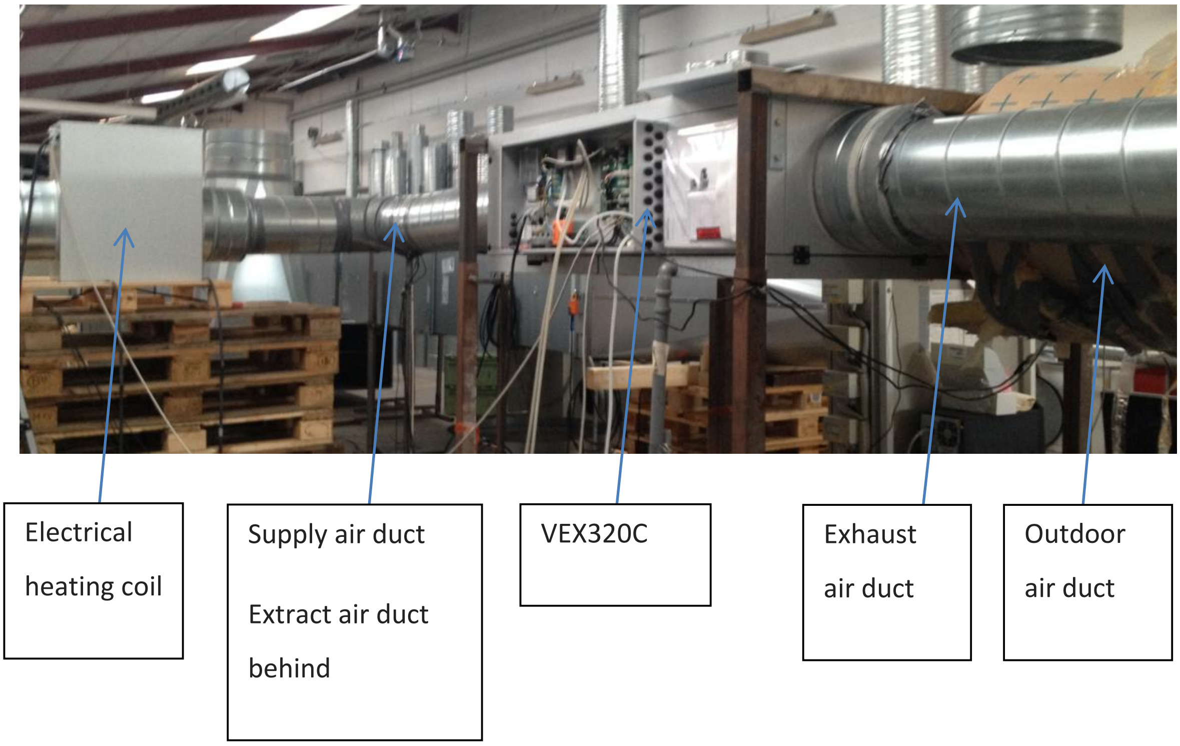

Figure 1: The measuring setup at Exhausto

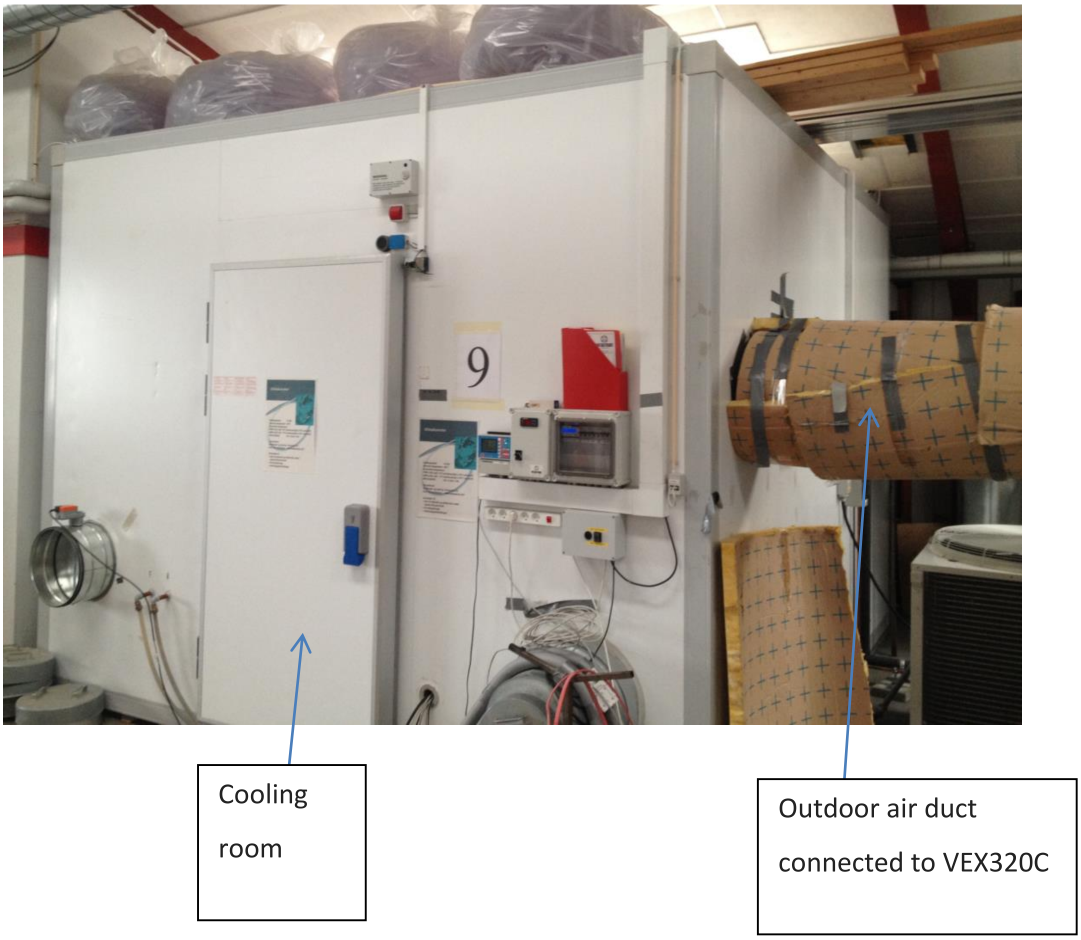

Figure 2: the cold air-supply from the cooling room to the VEX320C unit tested at Exhausto.

The VEX320C unit drags the extract air from the laboratory in which the measuring set-up is built. The exhaust air is delivered back to the room. The size of the laboratory is app. 60m x 10 m. Due to the large volume of the laboratory there are no signs of deviations in the room temperature and the humidity in the laboratory and therefore no changes in the extract air and the humidity in the extract air in the VEX unit.

The VEX320C drags the outdoor air from the cooling room as shown in the photo in Figure 2. The supply air is led back to the cooling room in order to reduce any icing up of the evaporators (cooling coils) in the cooling room, and because we would see a gradually dewatering of the room air in the laboratory.

The cooling room can produce air down to -35°C. The cooling room is built with two separate cooling units, one unit is fully controllable and the other unit is switched on in a fixed step. The cooling room has its own automatic control, in which the temperature of the cooling room can be set and if testing over a longer period fixed times for de-icing of the evaporators can be set in a week-clock.

Measuring equipment

Figure 3: temperature measurement set up

In each duct a temperature measuring cross is mounted, as shown in Figure 3. The temperature measuring cross consists of 5 pieces of PT100 sensors, placed in a measuring gross worked out according to EN308.

The temperature sensors turns the sensor head against the air string, in order for them to meet the air flow directly and not be influenced by any would-be own heating.

Each single temperature sensor has been calibrated as a measuring package incl. data logger. This means that the measured value in the data sheet (Excel) is calibrated via a JOPFRA temperature calibrator.

On the supply air, a temperature measuring cross is mounted both before the electrical heating coil (meaning after the temperature heat recovery) and after the electrical heating coil.

Air humidity is measured in the extract air and in the outdoor air via external calibrated humidity sensors.

Flow is measured in the extract air and in the supply air after the electrical heating coil via external calibrated flow measuring probes.

Data from above measuring equipment was logged via EXHAUSTO temperature measuring stand and transported to EXCEL sheet.

Figure 4: Exhauto data logging (left) and measuring stand (right)

The following equipment was used:

24 pieces of stk. PT100 temperature sensors

- Temperature calibrator: Make: JOFRA, type: ATC-155B, serie nr.: 508765-00259
- 2 pieces humidity sensors: Make: Testo, type: Hygrotest 6337 6974

- 1 piece flow measuring pipe: Make: MFS-C-200, Danak calibration number: 9-8-4507
- 1 piece of flow measuring pipe: Type: MFS-C-160, Danak calibration number: 9-8-4508
- 1 piece of pressure transmitter. Make: Halstrup, type: PU, serie nr.: 160694100002
- 1 piece of pressure transmitter, Make: Halstrup, type: PU, serie nr.: 9002.1398 KC51296

VEX320C:

The VEX320C has its own temperature sensors in all ducts of the units, after the electrical heating coil and has a Tice temperature sensor.

Furthermore a pressure transducer for registering the pressure loss through the counter flow exchanger on the extract air is mounted. This value is used in the control to control the de-icing process, when mounted and configured – if not the Tice sensor is used. Furthermore, a flow measuring device is mounted at both fans in the VEX320C.

During the preliminary tests with the measuring set-up we quickly determined that the flow measuring at the extract air was disturbed by condensate running into the nozzles in the inlet ring to the fan. This consequently let to heavily faulted measurements of the extract air volume. Blowing air into the tubes and nozzles used for the flow measurements in order to blow away the condensate only showed a temporary effect. The extract air volume is used for reference of the pressure loss through the counter flow heat exchanger in dry position, and after that to set a limit for actual time for de-icing. Thus, incorrect measurements of the extract air makes it is impossible to carry out the testing, as the proper control for the de-icing process no longer exists.

To carry out the tests the external flow measuring probe in the extract air was connected to the pressure transducer in the VEX320C control unit. The calibrated measuring values for the flow measuring probe were added to the VEX320C control software. The result of this adaption is a more precise measuring of the extract air when the test was made.

The VEX320C control unit was connected to the software module Lodam Multitool, which logged the following parameters from the VEX320C control unit each 10th second:

- Supply air volume
- Extract air volume
- Supply air temperature
- Extract air temperature
- Control signal to electrical heating coil (0-100%)
- Pressure loss through counter flow heat exchanger on extract air side
- Increase in pressure loss on the extract air side through the exchanger in comparison to exchanger in dry position
- Tice temperature
- De-icing steps

- Control signal for bypass damper

Basic settings/measuring carried out

The outdoor air temperatur – temperatur in the cooling room was set at -8°C. Requested air volume was set at 190l/s. Requested supply air temperature was set at 16°C.

Actual extract air temperature was 20-21°C with a humidity of 50-55%RF. The test was carried out over 3 days, and the extract air temperature incl. humidity was within above mention span, which is seen as very stable and therefore has no influence on the uncertainty in the results of the measurements.

The humidity in the outdoor air was very fluctuating from 70 to 90% (the air is gradually dried out due to condensation via ice on the evaporators). This parameter has no influence on the test (energy in the outdoor air is only changed due to the temperature changes, as no evaporation or condensation takes place in the counter flow heat exchanger on the supply air and is not part of the estimations of the test results.

The unit ran with pressure controlled ice-detection with a set-value of 45% pressure loss increase in relation to the exchanger in dry position. The unit was set for by-pass de-icing followed by reduction of the supply air. The unit therefore starts by-pass de-icing until the requested supply air temperature no longer can be kept. After that, the unit operates with reduced supply air.

Three tests were carried out:

1. With coated exchanger. The test was started on September 1st at 15.00 and finished on the 2nd of September at 11.00
2. With standard exchanger. The test was started on September 2nd at 15.00 and finished on September 3rd at 11.00.
3. With coated exchanger. The test was started on September 3rd, at 15.00 and finished on September 4th, at 11.00

Results from test run 1

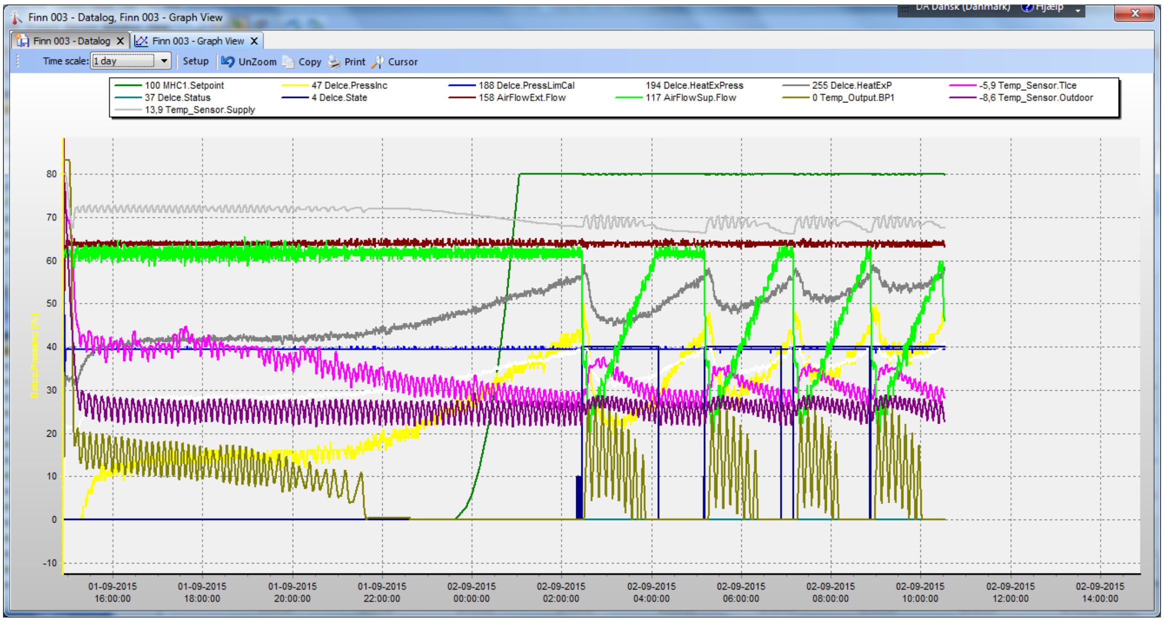

Figure 5: Graph showing the recorded values of temperatures, flows, pressure etc. for Test run 1.

The VEX unit is running from 3 PM to 2:30 AM (11.5 hours) before de-icing of the counter flow heat exchanger starts, meaning when the pressure loss from the extract air of the counter flow heat exchanger is increased by 45% in relation to the counter flow heat exchanger in dry position. After this, regular de-icing cycles are carried out and the distance between each cycle is currently minimized.

Results from test run 2

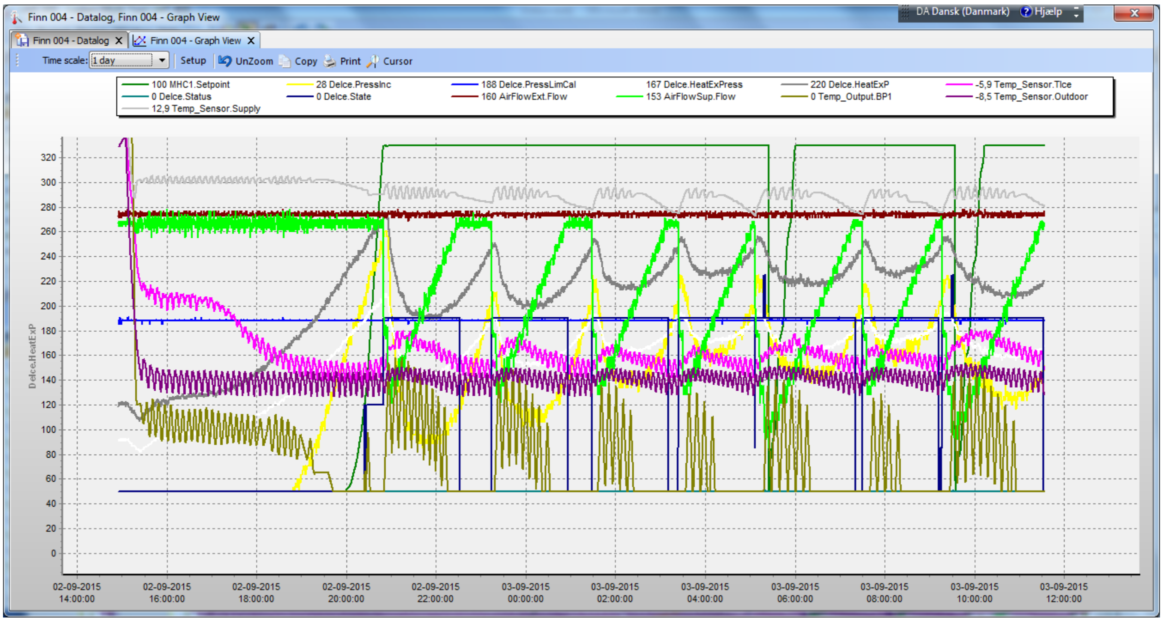

Figure 6: Graph showing the recorded values of temperatures, flows, pressure etc. for Test run 2.

The VEX-unit ran from 3 PM till 8:45 PM (5.75 hours) before de-icing of the counter flow heat exchanger started, meaning when the pressure loss on the extract air side had increased by 45% in comparison to counter flow heat exchanger in dry position. After this regular de-icing cycles are carried through and the distance between each cycle is minimized.

Results from test run 3

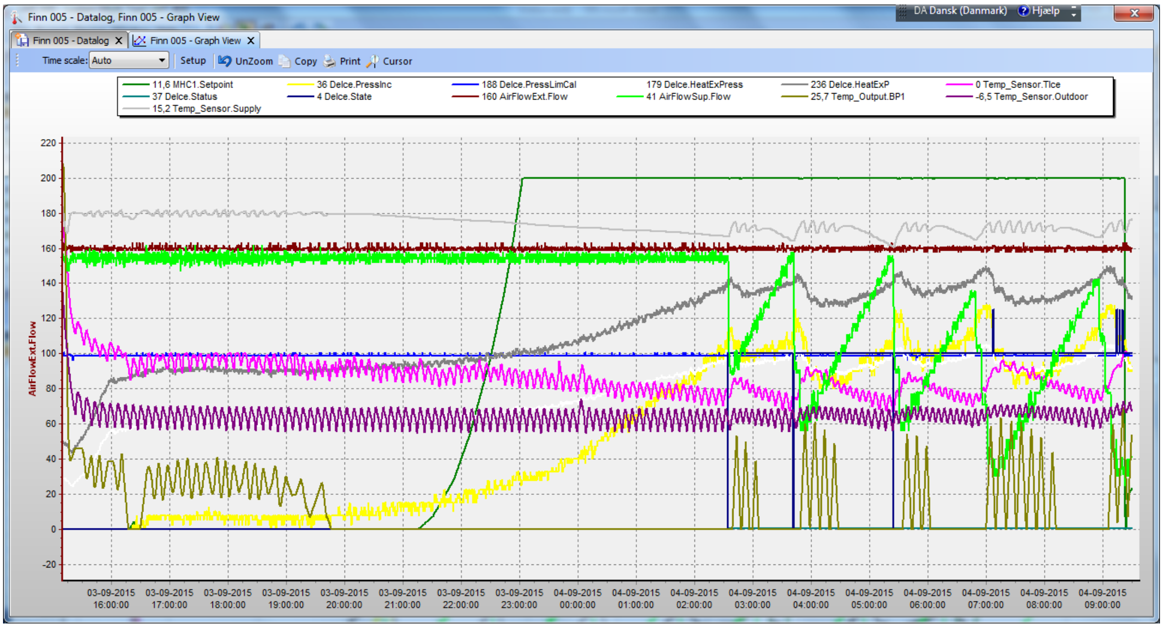

Figure 7: Graph showing the recorded values of temperatures, flows, pressure etc. for Test run 3.

The VEX managed once again to run from 3 PM until 2.30 AM (11.5 hours) before de-icing of counter flow heat exchanger starts up, meaning where the pressure loss on the extract air side of the counter flow heat exchanger has increaed by 45% in comparison to the counter flow heat exchanger in dry position. After this regular de-icing cycles are carried out.

Results from the measuring stand

Table 1: results from the measuring stand

25					Tilluft			Fraluft										[°C]	[Pa]
T11	T21	T22	T22-HE	T12	Pm	m3/h ved 20°	kg/h	Pm	m3/h ved 20°	kg/h	h_t	Effektafvigelse	Pa[fraluft]	Pa[indbl]	Δpa [indbl-fralu	Fugtighed 11	Fugtighed 21	20,630	
20,630	9,371	20,432	21,208	19,312	-2,04	0	0,00	0,7259625	48	58,30	0,98	#DIV/0!	0,00	0,00	0,00	48,08	99,81		
20,2	-7,9	13,0	13,4	6,3	34	565	680,97	95	561	675,71	0,74	#DIV/0!	0	0	0	54,04673	70,45009	Nano coated veksler i VEX320C	
20,7	-8,8	12,8	13,2	6,5	34	569	685,61	97	564	679,63	0,73	#DIV/0!	0	0	0	52,42466	89,78448	Standard veksler i VEX320C	

Table 1 shows the results from the measuring stand. The abbreviations are explained below.

- T11: Extract temperatur in 5-point measuring cross
- T21: Outdoor air temperature in 5-point measuring cross
- T22: Supply air in 5-point measuring cros safter VEX320C.

- T22-HE: Supply air in 4-point measuring cross after the electrical heating coil
- T21: Exhaust temperatur in 5-point measuring cross
- Supply air: Supply air volume at 20°C/mass flow
- Extract air: Extract air volume at 20°C/mass flow
- h_t: Temperature efficiency at 45% pressure loss increase through the counter flow heat exchanger
- Humidity 11: Relative humidity % in extract air duct
- Humidity 21: Relative humidity % in outdoor air

Judging the results:

The tests show:

- The coated exchanger are in both tests (test run 1 and 3) capable of running full heat recovery and no de-icing cycles in 11.5 hours
- The standard exchanger runs for full heat recovery and no de-icing cycles for 5.75 hours

The start pressure loss through the coated and the standard exchanger is at 92-93Pa (test run 2 and 3).

In test run 1, condensate had already built up in the exchanger (start pressure loss was a app. 120 Pa, the condensate originated from previous preliminary tests to adjust the settings). Thus it was necessary to carry out test run 3 to have a test starting from a dry heat exchanger.

From the results, it can be seen that there is no significant performance difference between the two exchangers (coated versus uncoated), when the counter flow heat exchanger has been iced up and the de-icing cycle has run. In real life application, it will often be the case that the heat exchanger gradually ices up during night hours, where the outdoor temperature initiate icing. During the day hours, where the outdoor temperature is rising, the ice will often naturally be removed leaving a coated exchanger with no ice for the next night. Thus, under such conditions, the coated heat exchanger will have a significant advantage. If the positive characteristics on the coated exchanger are to be prevailed at a permanent low outdoor temperature, generating ice in the counter flow heat exchanger it must be considered to change the de-icing flow in a way that completely de-ices the counter flow heat exchanger before the VEX-unit is controlled back to normal operation. This in order to take advantage of the long period that it takes to ice up a dry, coated exchanger.

Furthermore, we have determined that the temperature efficiency is the same for the coated and the standard exchanger, when the pressure loss through the exchanger on the extract air side is increased by 45% in comparison to the dry set-up.

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Figure 8: Photos of the counter flow heat exchanger shortly after test drive 1

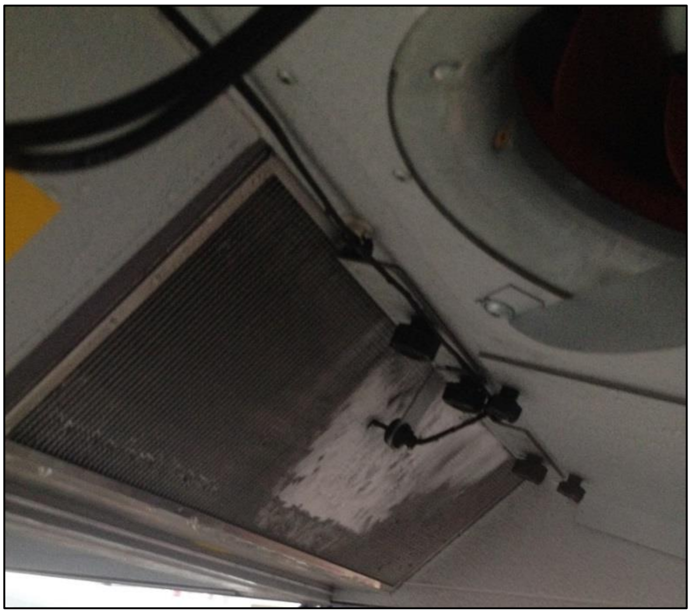

Figure 9: Photos of the counter flow heat exchanger shortly after test drive 2

Partial conclusion

The coated exchanger has a significant advantage concerning icing up, when the exchanger comes from a state with no ice. In the test the operation time for the VEX320 unit was increased from 5.75 hours to 11.5 hours before the unit needed to start de-icing.

For further optimizing a change of the de-icing flow should be considered, in order for the coated exchanger to become 100% de-iced before the unit returns to normal operation.

The pressure loss through a dry exchanger is the same for the coated and the standard exchanger. The temperature efficiency is the same, when the exchangers are iced up and the pressure loss increase of 45% in comparison to dry.

Demonstration of Anti-freezing surfaces at LU-VE

Introduction

This section contains the results from the tests of frosting on an aero-evaporator with fins with the following surface treatment:

"Micro-nanostructured surface prepared by etching the sample in hydrochloric acid and subsequent application of a perfluoroalkyl silane monolayer" and with a wetting angle of 151.8±3.9° - 150.8±1.5°.

The unit installed is the F30HC 611N7, having a capacity of 1650 W (in the conditions SC2), a fan of diameter 300 mm, finned surface of 5.9 m^2, fin spacing of 7 mm, an air flow rate of about 1550 m^3/h (air velocity 2.7 m/s).

Description of the experimental plant

The experimental test will be conducted in a calorimetric room having an air handling system inside, so as to maintain constant the temperature and relative humidity; also an inverter system allows to maintain constant the pressure (temperature) evaporation during the test frosting.

Figure 10: Unit in calorimeter room

The instrumentation of the chamber consists of a series of thermocouples for measuring the temperature of the air and the refrigerant side (R507A), pressure transducers and flow meters for measuring the mass flow rate.

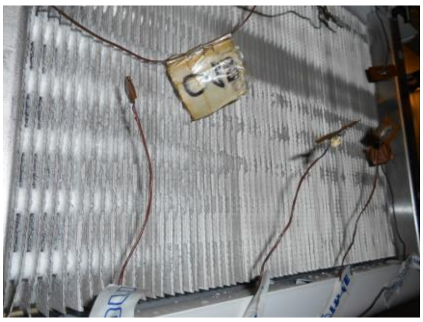

Figure 11: Finned surface – air inlet side

The uncertainties on the measurement of heat capacity are within ± 4%.

Analysis of the experimental data

The result of the experimental frosting test is shown in Figure 12, where the abscissa is indicating the time of frosting, whereas the ordinate shows the cooling capacity. When the formation of frost on the fins increases, the cooling capacity decreases, in a characteristic pattern, rising at the beginning of the entry of moisture in the room and then gradually decreasing almost linearly. The initial portion of lift depends on the thermo-hygrometric conditions of the air introduced in the finned pack. For example, at low temperatures such a phenomenon is almost imperceptible.

The ambient test conditions are: temperature of the air entering the finned pack 2.8 °C and relative humidity 78%.

The refrigeration cycle processes R407A refrigerant with the evaporation temperature to -7.8 °C, condensing temperature of 36.6 °C, and the liquid temperature upstream lamination valve 29 °C.

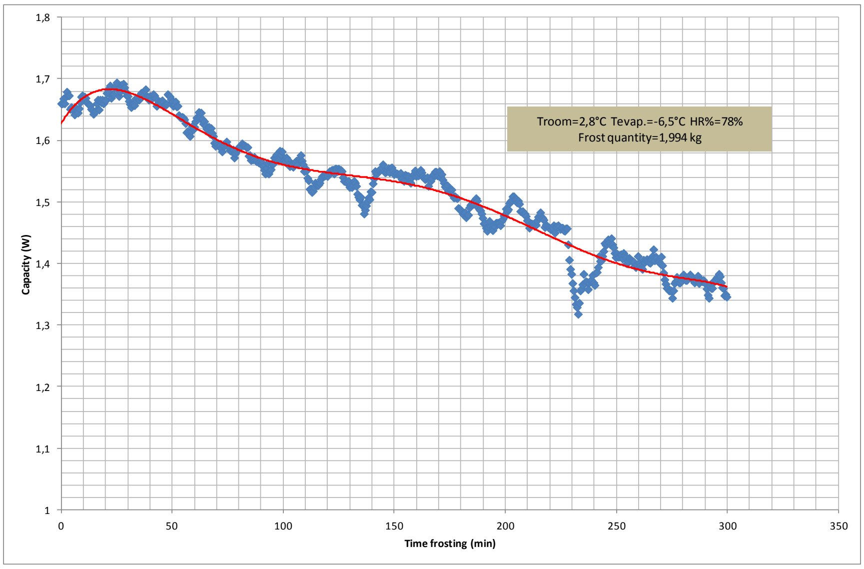

Figure 12: Cooling capacity – Frosting time (nano-structured surface)

In Figure 13 we can see an enlargement of the formation of frost on the fins in the air inlet area. In this area of the finned pack, the temperature of the fins is higher compared to the more central parts, as the refrigerant enters phase of super-heating during the evaporation process (necessary to preserve the compressor from possible injections of drops of liquid). The structure of the frost is very different from a the frost formation on a "standard" unit (see fins collar - uniform layer).Thanks to the super-hydrophobicity of the surface, a high roughness, created by small frozen drops, is observed.

On the air outlet side (Figure 14), where the temperature and humidity of the air are different from the input air, there is a structure of aggregation of the ice crystals, which is more uniform on the fins.

Conditions on the air inlet side : T = + 2.8 ° C RH = 78% x = 3.6 g/kg T_{fluid} = -3.5 ° C

Conditions on the air outlet side: T = -0.5 ° C RH = 89% x = 3.2 g/kg T_{fluid} = -6.5 ° C.

Figure 13: Particular fins – air inlet side

Figure 14: Particular fins – air outlet side

The table shown in Figure 15 shows the numerical results of the tests on nano-structured and standard fins. The columns are the following information (in order from left to right): model unit, fin type, test conditions, cooling capacity: initial and final, time frosting, energy removed from the room (E), amount of frost deposited (FF), energy and amount frost ratio and finally, the comparison tests.

Experimental data										Comparison		
				Capacity								
Model	Configuration	Test condition	DT1	Initial	final	Time frosting	Energy	Frost Formation	Ratio E/FF	Ratio E/FF		Ratio E/FF
		°C/%/°C	°C	W	W	min	MJ	kg	MJ/kg	MJ/kg	Ratio	MJ/kg
		(Troom/HR/Tev)	(Troom-Tev)					experimental	experimental			
F30HC 611E7	Surface nanostructured (1)	2,8/78/-6,5	9,3	1650	1360	300	27,1	1,99	13,6			**13,6**
F30HC 622E7	Standard	3,9/83/-9,95	13,9	6450	3540	220	65,9	7,40	8,9	9,14	0,80	11,18
F30HC 622E7	Standard	0,3/91/-7,8	8,1	5100	2450	180	40,8	4,60	8,9	8,66	0,76	11,74
F30HC 622E7	Standard	1,4/93/-9,97	11,4	6500	3050	185	53,0	6,40	8,3	8,79	0,77	10,81
F35HC 84E6	Standard	0/81/-10	10,0	4000	2680	170	34,1	3,00	11,4	12,1	1,05	10,76
F30HC 611E7	Standard	2,8/78/-6,5	9,3	1570	940	300	22,6	1,94	11,6	11,47	1,00	11,64
											ā	**11,12**
(1)											σ	0,45
Micro-/nanostructured surface prepared by etching the sample in hydrochloric acid and subsequent application of a perfluoroalkyl silane monolayer. (151.8±3.9°/150.8±1.5°)											σm	0,23
											3σm	**0,68**
											Δr	**6%**
											Delta	**-18%**

Figure 15: Summary table comparing units with and without nano-treatment

The comparison was performed under the same test conditions for the unit with nano-structured fins and the unit with standard fins.

The comparison was performed based on the ratio of the cooling energy (E) removed from the chamber by the unit under test and the amount of frost (FF) that is formed between the fins. This relationship is evident in the last column to the right in Figure 15.

Units with standard fins have a value of E / FF equal to 11.12 MJ / kg, while the unit with fins nano-structured 13.6 MJ / kg. This means that for the same energy removed from the room, there is less frost formation, estimated at about 18% (relative error = ± 6%) for the unit with nanostructured fins compared to a standard unit.

Partial conclusion

The reduction of frost formation using nano-structured fins, assembled on a complete unit (aero-evaporator), reached values of approximately **18%**.

This result is in line with the results from the tests made on the same type of fins (-17%), but in a much smaller coil structure (Report on February 2015); this test approach was necessary, for the first difficulties in the treatment of large areas.

Demonstration of heat exchangers with refrigerant fluid phase change at DTI

Introduction

The objective of the test is to investigate the long-term influence of being exposed to liquid ammonia on a TiO_2 coated heat exchanger with 500 nm features (evaporator). The heat exchanger is a shell and plate heat exchanger from Vahterus with water on the plate side and liquid ammonia on the shell side of the heat exchanger. The two flows are counter directional.

Operating conditions

The operating parameters of the evaporator were regulated to the following conditions:

Plate side
Fluid: 30% ethylene glycol/water
Flow: 2086 l/h
Entering temperature: 12.2 °C
Shell side
Fluid: Ammonia
Flow, cold side: 47.6 kg/h
Entering temperature: 10.6 °C
Target energy transfer: 4 kW

Test setup

The heat exchanger was placed alongside the existing ENE-HVAC test rig as an external apparatus. By control of the temperatures and the flow rates to the two sides of the heat exchanger, the heat transfer, expressed as the evaporator UA-value, could be determined.

The ethylene glycol/water mixture was reconditioned to the desired inlet temperature by means of an electric heating element. The ammonia was reconditioned to the desired inlet temperature by external cooling in a condensing heat exchanger and a sub-cooling heat exchanger respectively.

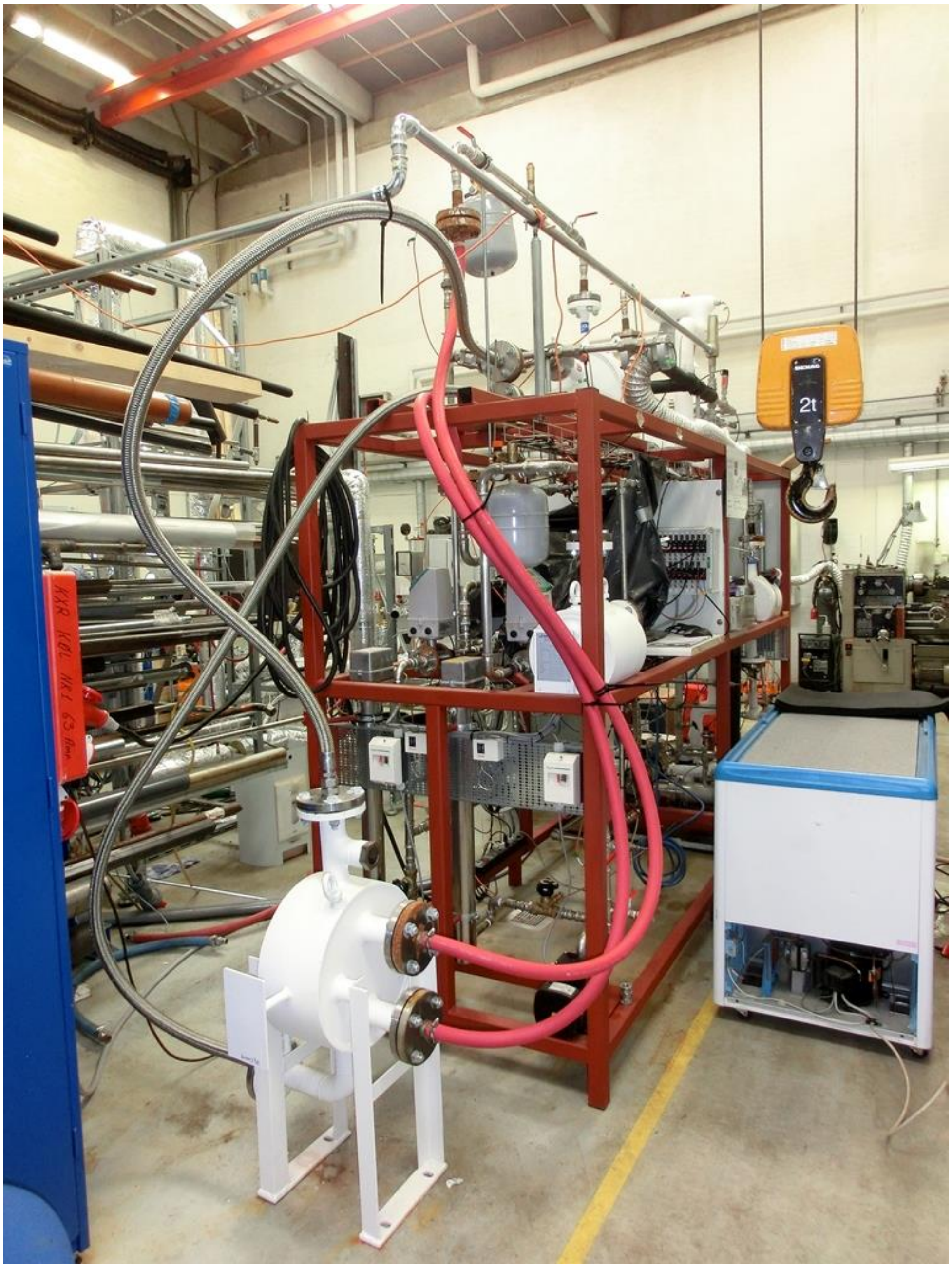

Figure 16: Test setup

Test results

The test was running continuously for a period of 58 days. During the test period, adjustments have been made to match the pre-determined operating conditions.

Table 2: Selected results from the 58 day demonstration of the structured Vahterus heat exchanger

	Values: Start of test	Values: End of test	Numeric deviation	Deviation In %
Evaporation temperature [°C]	10,8	11,2	0,43	
Brine outlet temperature [°C]	12,3	12,6	0,27	
Brine inlet temperature [°C]	14,2	14,2	-0,04	
Brine flow [l/hr]	2084	2087	2,97	0,1%
NH_3 flow [kg/hr]	37,8	38,4	0,53	1,4%
Log. mean temperature difference [K]	2,3	2,0	-0,28	-12,1%
Total heat transfer [W]	3955	3333	-622	-15,7%
UA [W/K]	1699	1638	-60	-3,5%

Partial conclusion

The results listed in Table 2 show a significant drop in the total heat transfer. As the total heat transfer is influenced by several other parameters, it might not be the optimum parameter for evaluating the condition of the heat exchanger. The values at the start and at the end of the test period are derived as an average over several minutes at stable operating conditions.

The results obtained during this test are not comparable with the results obtained by Vahterus in that both temperatures and capacities are significantly different. It has not been possible in practice to copy the Vahterus operating conditions in this test.

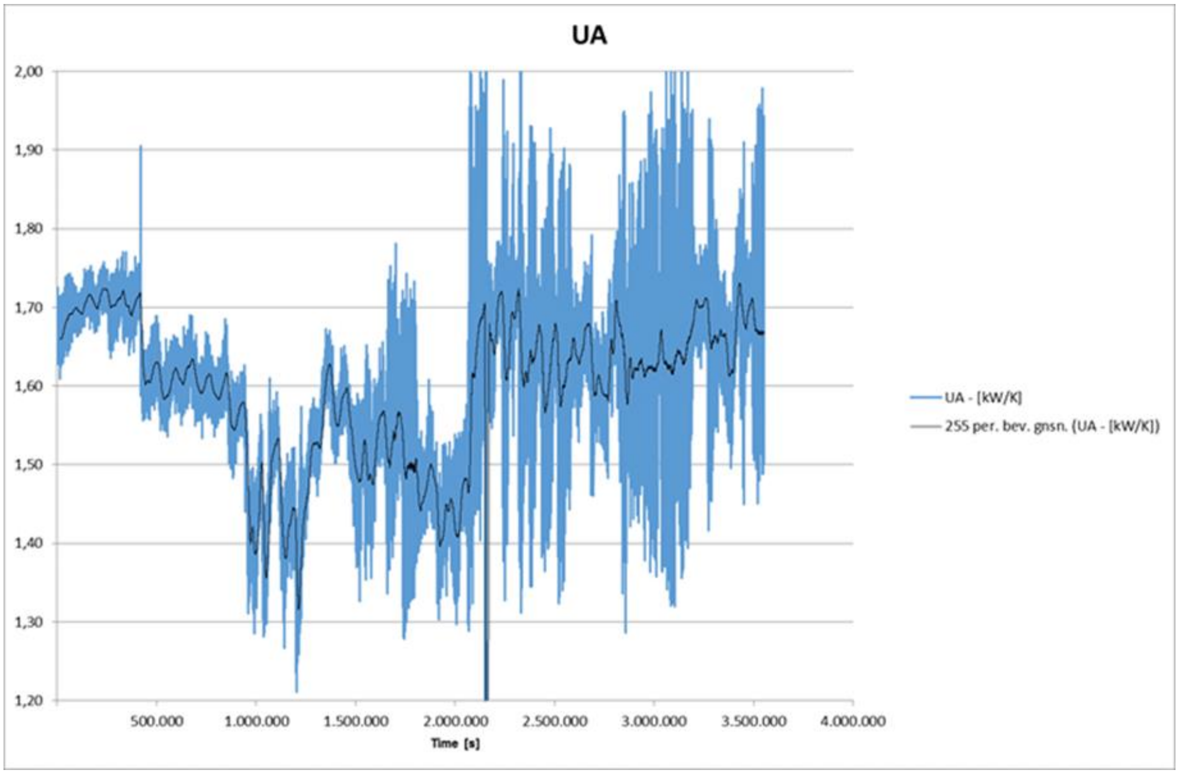

Figure 17: UA-value progression

When using the evaporator, the UA-value gives a more undistorted parameter for the evaluation. The UA-value is plotted as a function of time in Figure 17. During the test period of 58 days, the test rig has partly been operated as unattended. This means that the parameters have been allowed to drift, and they have been corrected back to the start values on a random basis. This explains the variation seen in the UA-value during the 58 days.

A decrease of the UA-value by 3.5% from the start to the end of the testing period probably indicates that no deterioration of the heat exchanger coating has occurred. The difference between the start and the end of the test period can be explained by the fact that the start and the end conditions have not been replicated 100%.