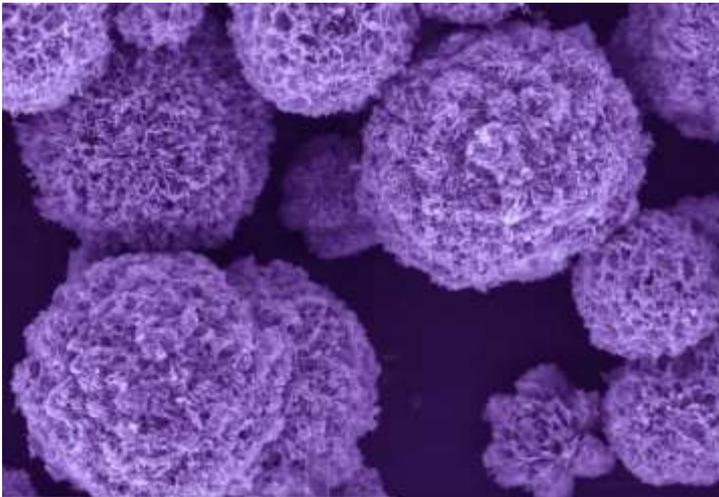
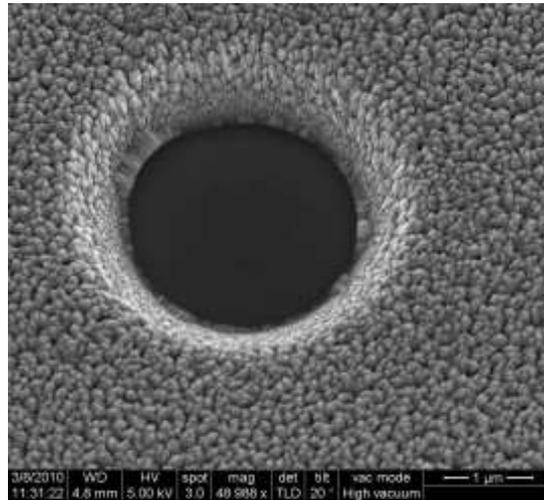


Publishable report

EnE-HVAC - Energy Efficient Heat Exchangers for HVAC Applications



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4.1 Final publishable summary report

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4.1.1 Executive summary

The objective of the EnE-HVAC project has been to develop novel nanotechnological approaches to achieve a significant reduction of the energy requirements for HVAC (heating, ventilation and air-conditioning) systems. To achieve these savings, the EnE-HVAC project approaches all aspects of the HVAC system, developing solutions for improving heat transfer and transport throughout the whole system.

During the project, three technological approaches have been brought into play to enhance the overall energy efficiency of the complete HVAC systems.

Nanotechnological coatings limiting ice formation on HVAC systems

Frost formation on the surface of heat exchangers is a great challenge for the energy efficiency. Periodic defrosting by heating is required, but that consumes energy. A heat pump requires app. 13% of the total energy consumption of the heat pump for periodic defrosting at ambient temperatures below +7°C. Even if frost formation is not prevented completely, longer cycles between de-icing intervals would save energy significantly.

Through this project, super hydrophobic coating systems have been developed to slow the formation and spreading of ice on cooled surfaces. These systems have been developed through extensive laboratory development at Danish Technological Institute (DTI) and Tekniker IK 4, in close collaboration with Luve S.p.A., EXHAUSTO A/S and DVI A/S. Further testing of these surfaces in full-scale heat exchanger systems at EXHAUSTO and Luve have shown a significant delay of ice formation. At EXHAUSTO, the run time between de-icing intervals was increased from 5:45h to 11:30h, and ice formation on systems from Luve was decreased by 18%.

Nanostructured surfaces for increased heat transfer in refrigeration systems

When improving heat exchanger efficiencies of evaporators and condensers, it is important to look at how the boiling behaviour of these systems can be optimised in order to give a decreased energy consumption.

Through this project, nano- and microstructured surfaces as well as sol-gel based surface coatings have been developed to increase the boiling efficiency of refrigerant-based heat exchanger systems, and the overall performance and energy efficiency of these systems has been increased. Through laboratory development at DTI and Tekniker IK4, surfaces showing a significant improvement in boiling heat transfer for both CO₂ and NH₃ was developed. These systems were scaled for application on full-size heat exchangers at Vahterus Oy and an increased efficiency of 8% was shown for NH₃ systems.

Development of nanofluids for increased efficiency of brine systems

The objective of this work was to develop nanofluids to improve the heat transfer across heat exchanging surfaces. Nanofluids are nanoscale colloidal suspensions containing condensed nanomaterial in a fluid. The potential of doping refrigerants with nanoparticles to increase the heat transfer from a heat exchanger surface to the refrigerant has been investigated. Development on nanodiamonds from Carbodeon Oy have been made to enable suspension of these in the refrigerants CO₂ and NH₃. For NH₃ surface modifications were found to enable this suspension, but unfortunately no significant effects were observed for the boiling behaviour. In addition, nanoparticle doped brine systems were investigated but had no significant effect on the heat transfer.

To support the approaches above, ESI software Germany GmbH has developed simulation models for prediction of performance on heat exchanger systems with improved surfaces and/or refrigerants.

4.1.2 Summary description of the project

The EnE-HVAC project will achieve significant energy savings in future Heating, Ventilation, and Air Conditioning (HVAC) systems via new and innovative technologies. These technologies include nanotechnological coatings and various types of surface treatment for improved heat transfer; new nano- and micro-materials for improved efficiency of the refrigerants, and improved efficiency and heat transfer capabilities of coolants via new nanotechnological additives.

These goals can be realised by tackling the efficiencies in all parts of the HVAC systems. The technologies used will address the heat exchanger efficiency on both the air and liquid side of heat exchangers such as condensers/evaporators and on heat recovery systems. Furthermore, this project will address the heat transport system to ensure high efficiency throughout the HVAC system. In order to obtain such large energy demands, heavy demands will be made on the refrigerants that are used; to ensure the largest possible environmental effects, there will be significant focus on the use of “green” refrigerants avoiding HFC and CFC gasses throughout the project.

To decrease the overall energy demand, it is vital to look for new and innovative technologies to increase the efficiency of currently applied state-of-the-art HVAC systems. These new technologies are:

- Nanostructured coatings including sol-gels and PVD coatings for increased heat transfer.
- Nanotechnological coatings with anti-freezing properties to limit over-icing of heat exchangers.
- Nanofluids for the improvement of heat transport.

Figure 1 below illustrates where these nanotechnological approaches are required to improve the energy efficiency of the HVAC system.

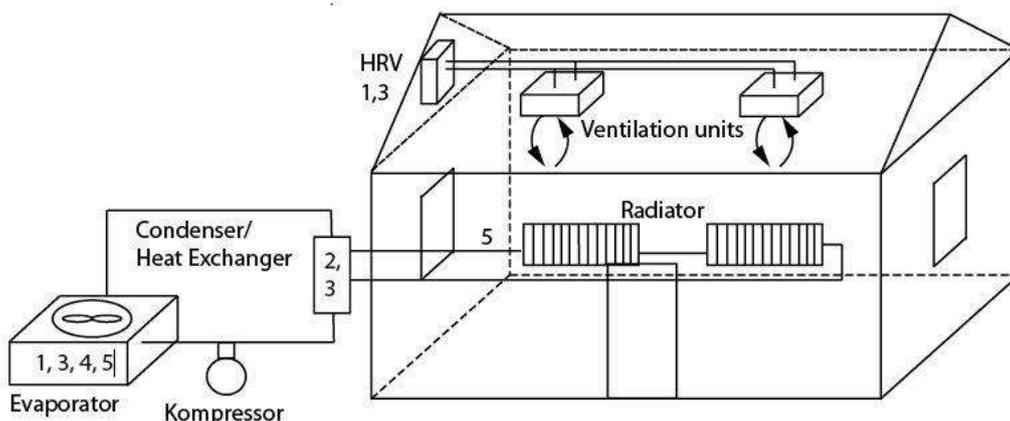


Figure 1: Schematic overview of the components to optimize with 1: Anti-freezing/anti-ice surfaces, 2: Improved condensation, 3: Improved condensate drainage, 4: Improved evaporation, 5: Improved heat transport

The nanotechnological coatings will be applied on the air side of the air-air as well as the liquid-air heat exchangers. Sol-gel coatings that significantly will decrease ice formation and adhesion to heat exchanger fins are being developed at the two research institutes: Teknologisk Institut (Denmark) and IK4 Tekniker (Spain). These can be heat exchangers and heat pumps used for residential or commercial buildings, where ice formation can be a large problem. By avoiding ice formation or ice adhesion, de-icing cycles can be minimized or completely avoided thus giving rise to significant energy savings. To ensure the best performance and applications, Italian LuVe S.p.a, Danish “Dansk Varmepumpe Industri” and EXHAUSTO A/S are included in the consortium to help develop and demonstrate the technologies.



Ice formation on air fins from EXHAUSTO A/S heat exchanger.

On the refrigerant side of liquid-air and liquid-liquid heat exchangers, there are two approaches for improving heat transfer. In boiling heat transfer, micro- and nano-structured surfaces will be developed at Danish Technological Institute to achieve large increases in the boiling efficiencies of the refrigerants and in that way allow for a reduced energy usage. Sol-gels developed at IK4 Tekniker will also be applied on the liquid side of heat exchangers. By manipulating the polarity of these surfaces, the wetting capabilities and thus the heat transfer capabilities of both refrigerant and brine can be improved. Again, relevant heat exchanger manufactures and developers are an integrated part of the project consortium. Finnish Vahterus Oy will be producing and testing modified liquid-liquid heat exchangers, while Italian LuVe S.p.a and Danish “Dansk Varmepumpe Industri” focus on liquid-air heat exchangers for residential and commercial applications.

A third approach to increasing the efficiencies of the heat transfer is the use of nanodiamonds from the Finnish company Carbodeon Oy. Nanodiamonds have shown promise for increasing heat transfer in heat exchanger applications. Using single digit nanodiamonds developed at Carbodeon we expect to achieve significant increases in the efficiency of the refrigerant with very small amounts of nanodiamonds. This increase has previously been demonstrated in other refrigerants, but this project has focus on natural refrigerants such as CO₂ and NH₃. The addition of nanodiamonds to these refrigerants can only be achieved through a close collaboration with a company such as Carbodeon. The company has considerable control with the functionalities of the nanodiamonds and can therefore modify the diamonds to achieve the best possible results.



Dispersion of Nanodiamonds in liquid CO₂.

To maximize the output of the project, ESI group, the German pioneer in digital simulation software for prototyping and manufacturing processes that takes the physics of materials into account, is included in the project. The capability of tailoring surfaces towards specific physical/chemical properties will be assessed using ESI’s Multiphysics suite of solvers ACE+. Coupling nano-phenomena with large-scale heat transfer models and fine-tuning the surface structures toward achieving the desired goals (anti-ice surfaces / improved condensation / improved evaporation / enhanced heat transfer) will enable predictive modeling of surface effectiveness.

Accurate simulations of heat transfer accounting for nano-scale phenomena with models describing complete heat exchangers or other HVAC components require the modeling of unsteady free surface

flow driven by surface tension, turbulence, heat-transfer, buoyancy and phase-change. The computational simulation must be able to maintain stability, accuracy and low turnaround times.

The entire project was divided into different overlapping “phases” as illustrated in the figure below (Figure 2). The phases comprise:

- **Lab-scale** primarily focused on the development and test of the selected technologies at lab-scale.
- The **small tests** focused on scaling the technologies from laboratory samples to a scale where they can be applied on real heat exchangers.
- **Full-scale** is the phase where the technologies go from testing to real demonstration.

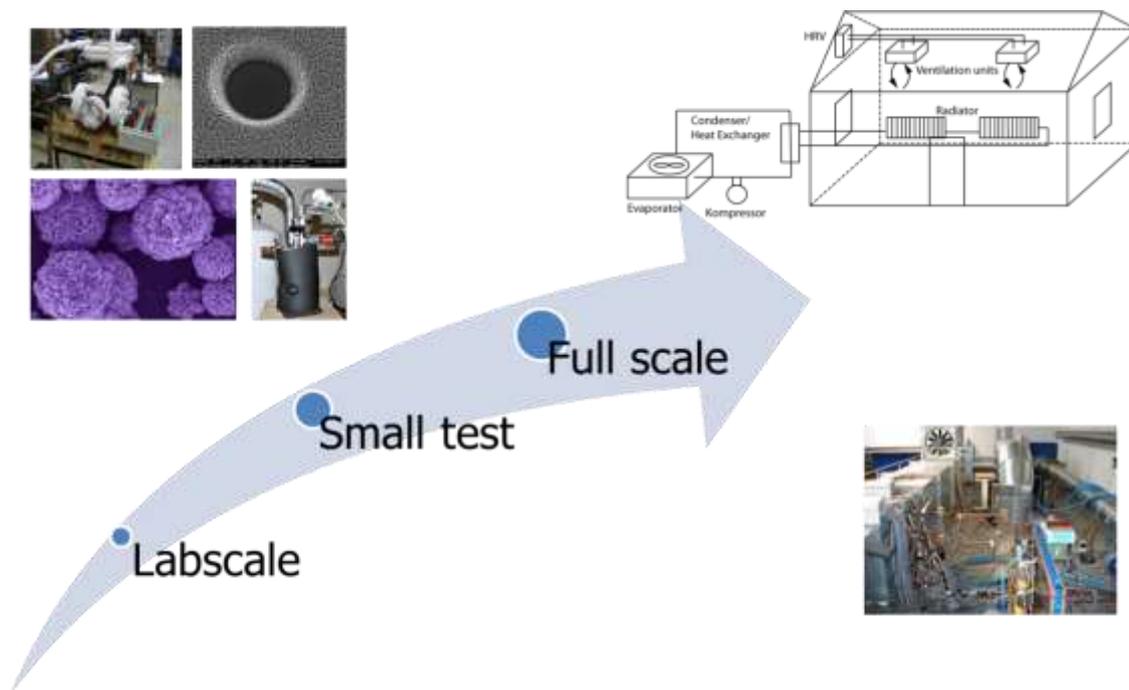


Figure 2: The EnE-HVAC project was divided into three overlapping phases going from lab-scale development over small-scale tests to full-scale tests and demonstration.

4.1.3 Description of the main S&T results/foregrounds

List of abbreviations used in this section

CAH	Contact Angle Hysteresis
CFD	Computational Fluid Dynamics
CO ₂	Carbon dioxide, green refrigerant
HVAC	Heating, Ventilation and Air-Conditioning
HRV	Heat Recovery Ventilation
HX	Heat Exchanger
IL	Ionic Liquid
LMTD	Log Mean Temperature Difference
ND	Nanodiamond
NH ₃	Ammonia, green refrigerant
NP	Nanoparticle
PCM	Phase Change Material
PDMS	Polydimethylsiloxane
PVD	Physical Vapour Deposition
TiO ₂	Titanium dioxide, material used for coatings and nanoparticles
WP	Work Package

4.1.3.1 Anti-ice surfaces

Anti-ice is an umbrella term for various approaches such as surfaces with low ice adhesion, surfaces that delay freezing (delay ice nucleation, freezing point depression) and surfaces that delay the spreading of frost when freezing eventually happens.

Icing problems that are in focus in the ENE-HVAC project

The project has focused on anti-ice surfaces for two types of heat exchangers:

- A. Air-to-refrigerant heat exchangers (finned tube heat exchangers, air coils) of heat pumps using outside air as heat source (evaporator in Figure 3, and Figure 4 shows a photo of a typical air-to-refrigerant heat exchanger). The heat exchanger fins are typically cooled below 0°C when the outside temperature is below app. +7°C. Similar heat exchangers with identical icing problems are applied in commercial refrigeration.
- B. Air-to-air counter-flow plate heat exchangers of heat recovery ventilation (HRV in Figure 3, and Figure 5 shows a photo of a typical air-to-air counter-flow heat exchanger). Different types of heat exchangers can be applied in HRV, but counter-flow heat exchangers have the highest efficiency. At outside temperatures below app. -3°C, the more humid outgoing air is cooled to temperatures below 0°C.

Frost accumulates on the surfaces of both of the described heat exchangers, subsequently blocking the flow. Periodic defrosting by heating is required, and that consumes energy. A heat pump requires app. 13% of the total energy consumption of the heat pump for periodic defrosting at ambient temperatures below +7°C. If frost formation cannot be completely prevented, longer cycles between de-icing intervals would significantly save energy.

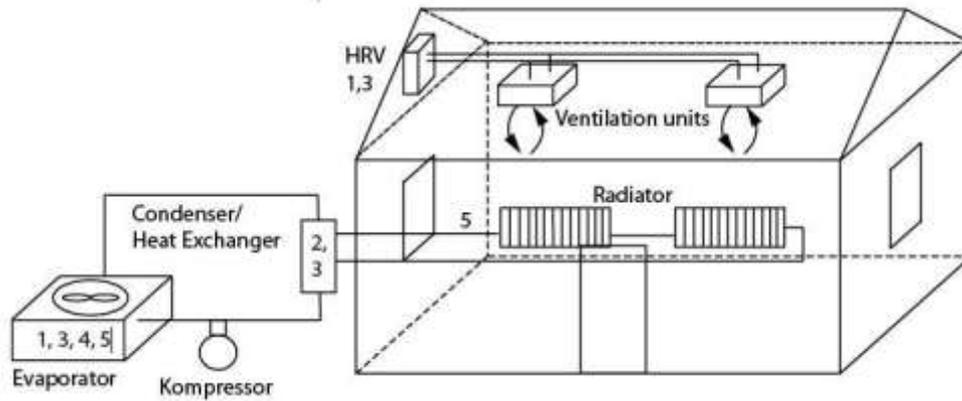


Figure 3: Schematic of a modern building with heat pump and heat recovery ventilation.



Figure 4: Typical heat exchanger for heat pumps and refrigeration.

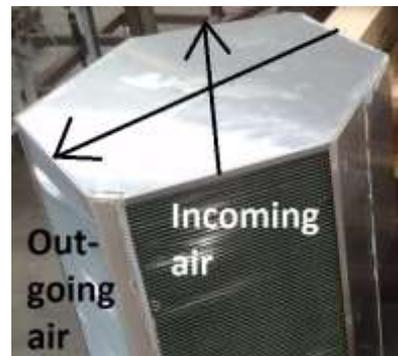


Figure 5: Aluminium counter-flow plate heat exchanger for heat recovery ventilation.

Coating development

Hydrophobic and superhydrophobic surfaces were developed to meet the specific requirements for anti-ice coatings. Smooth, hydrophobic surfaces were prepared by sol-gel processing from organosilanes and possibly additional organic precursors resulting in organic-inorganic hybrid coatings. Reactive (and therefore not leachable) silicone additives or perfluoroalkyl silanes were added in small concentrations. During curing, the additives orientate in a surface tension driven-process towards the surface as illustrated in Figure 6.

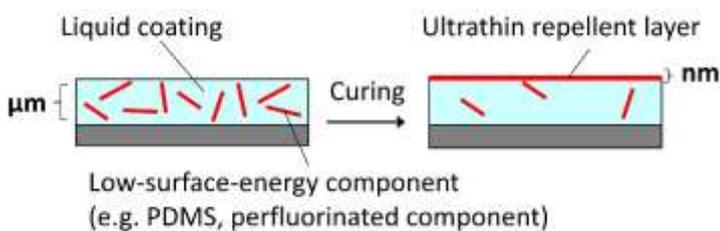


Figure 6: Preparation of a hydrophobic surface by a hydrophobic additive.

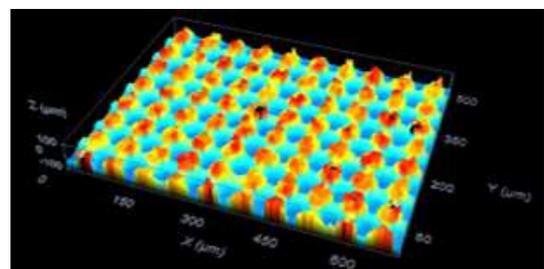


Figure 7: Height profile of a pyramidal structure on Al prepared by laser.

Structured surfaces were also developed and investigated. One process to prepare structured, super hydrophobic surfaces was to structure an aluminium coil material with laser and to apply a thin, hydrophobic sol-gel coating without compromising the structure. A height profile of a structured

aluminium surface with pyramidal structure is shown in Figure 7. An alternative method was to etch the aluminium and subsequently apply a hydrophobic perfluoroalkylsilane monolayer. As commercial reference materials, bare aluminium (used for heat exchangers today) and hydrophobic polymers (FEP, polypropylene, silicone rubber) were selected.

Wetting behaviour / Contact angles

The ability of a surface to reduce the spreading of frost can be predicted by advancing and receding contact angle measurements. The difference between the two angles, the contact angle hysteresis (CAH), should be as low as possible, and the absolute contact angles should be high. The prepared hydrophobic surfaces provided a CAH of only 10° and adv./rec. water contact angles of about $105^\circ/95^\circ$.

Superhydrophobic surfaces provide higher contact angles and lower CAH when drops are applied to a dry surface. However, the heat exchangers are continuously exposed to condensation of water. Small water drops usually condense inside the surface structure and compromise superhydrophobicity. Under these conditions, most superhydrophobic surfaces only perform as hydrophobic surfaces. Within the project, we successfully managed to prepare superhydrophobic surfaces that at least partly maintain the characteristic air-pocket (Cassie-Baxter) state under condensation. Surfaces providing water contact angles above 150° with solely 1° CAH in dry condition (see Figure 8) maintained in a special experiment simulating condensation adv./rec. angles of about $110^\circ/90^\circ$ (see Figure 9). Despite this improvement compared to the state-of-the-art, the superhydrophobic surfaces are still outperformed by the best smooth hydrophobic surfaces under condensation condition due to lower CAH.



Figure 8: Water drops rolling off a dry superhydrophobic surface.

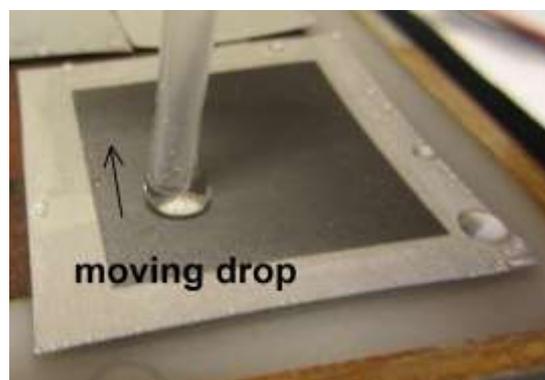


Figure 9: Superhydrophobic surface on cooling block to achieve continuous condensation of water. A water drop is guided with a pipette tip along the surface to simulate advancing and receding contact angles. The reflection of light at the bottom of the drop indicates that part of the airpockets still are present.

Anti-ice - Low ice adhesion

Surfaces with low surface energy can reduce the adhesion of ice. However, investigations within this project (see test device shown in Figure 10) led to the conclusion that even the reduced adhesion is too strong to detach frost with the airflow. Any application of additional mechanical aid, for example vibration, was expected to be too costly. Therefore, this approach was not pursued any further.



Figure 10: Ice adhesion test.

Anti-ice - Freeze delay ('freezing point depression')

Freezing (= ice nucleation) is a random process with a distinct probability. The freezing probability increases when the temperature decreases. Due to the random occurrence, a wet surface below 0°C cannot guarantee that no freezing occurs, but there might be a different average freeze delay for different surfaces. One surface might on average stay ice-free longer than another surface. To obtain realistic and significant results on freeze delay performance, we constructed an ice test chamber (see Figure 11). The ice test chamber secures permanent condensation of water on the sample surfaces throughout all experiments. We found that previous literature results are not comparable due to different testing techniques. Within the precision of our experiments, bare Aluminium and all other investigated surfaces including hydrophobic coatings performed within the same order of magnitude. Differences to bare Aluminium are not significant enough for exploitation on real devices. However, the test conditions had a strong influence on the ice formation temperature. Cooling a single water drop led to freezing between -16°C and -26°C, while freezing on a test plate with an about 3000 times larger surface (100 cm²) occurred between about -5°C and -11°C when cooled at a rate of 0.1°C/min. Real heat exchangers have an even larger surface of 1 to 500 m².

Anti-ice - Decreased frost spreading

As observed in the freeze delay experiments described above, freezing at temperatures above -10°C only occurs occasionally at single spots. However, when freezing occurs on bare Aluminium, the whole Aluminium surface freezes instantly. On hydrophobic surfaces, condensation forms single drops that are not in contact with each other. Therefore, frost spreading is delayed. Our results gave clear evidence that all hydrophobic surfaces somehow delay frost spreading, but that the more hydrophobic (low CAH, high contact angles) a surface is, the slower the frost spreading. In a frost spreading experiment, wet sample plates were maintained at -4°C in a +12°C/90% rel. humidity atmosphere. We induced freezing by placing a small lump of ice in the centre of the sample plates. On the hydrophobic coatings described above, with solely 10° CAH, freezing spread at a rate of only 2 µm/s. As shown by Figure 12, the plate stays mainly frost free within 20 min. even though ice is present. The effect is reproducible and sufficiently significant for technical exploitation.



Figure 11: Ice test chamber (sample plate is visible to the left).

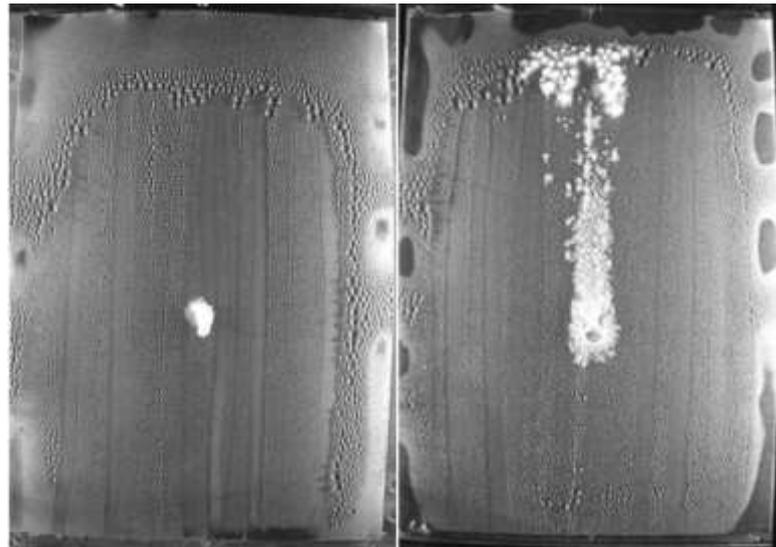


Figure 12: Plate with hydrophobic coating, 10 x 15 cm, maintained at -4°C, 20 min. after placing ice in the centre of the plate.

Figure 13: Same experiment as described for Fig. 10, but with an upward, forced air flow of 1 m/s.

However, in an additional experiment, we observed the following drawback. An airflow of 1 m/s, which corresponds to the velocity of the ventilation equipment, leads to rather fast frost spreading in the flow direction while frost spreading is still slow in all other directions, see Figure 13. That is why tests were needed on real devices to evaluate the applicability of the concept to inhibit frost spreading rather than freezing.

Anti-ice - HRV validation and demonstration

A plate heat exchanger for heat recovery ventilation, coated with the hydrophobic coating described above, was compared to an otherwise identical reference with a bare aluminium surface. In test runs under identical conditions (according to EN 308), the outgoing air on the cold side (this is where icing occurs) was cooled to approximately -5°C. The heat transfer of both heat exchangers was identical. The flow was kept constant by adjusting the fan power and the pressure drop was monitored. A pressure drop above 400-500 Pa indicates that the heat exchanger is blocked and that defrosting is necessary. As shown in Figure 14, the coating increased the time between defrosting cycles from about 1 h to about 2.3 h. On the reference sample, frost mainly forms inside between the plates. On the coated heat exchanger, water froze at and after the outlet, forming icicles as shown in Figure 15. The icicles do not necessarily block the flow. In a real installation, this performance would lead to considerable energy savings.

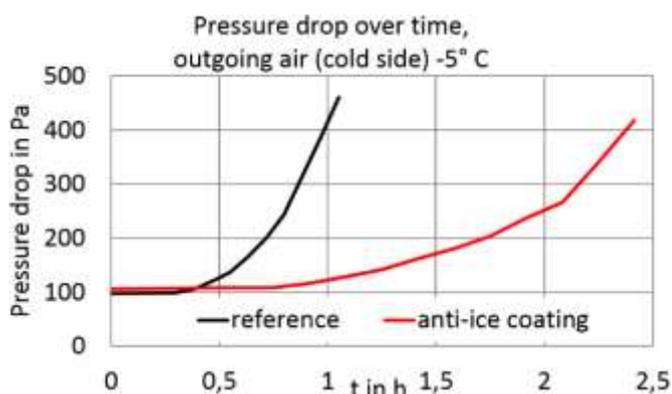


Figure 14: Test run with a heat exchanger with anti-ice coating and an uncoated reference showing the time until the pressure drop reaches about 450 Pa due to frost blocking the flow.



Figure 15: Icicles at the outlet of the heat exchanger with anti-ice coating.

The performance of a complete heat exchanger unit (VEX320C) was demonstrated. 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 reduced supply air. Therefore, the unit starts by-pass de-icing until the necessary supply air temperature no longer can be kept. After that, the unit operates with reduced supply air.

A coated as well as an uncoated heat exchanger were tested. Starting from a dry heat exchanger, the coated exchanger could run full heat recovery and no de-icing cycles for 11:30 hours whereas the standard exchanger only could run full heat recovery and no de-icing cycles for 5:45 hours. It was observed that a significant improvement in the time before de-icing is necessary for the anti-ice coated heat exchanger. There was no significant difference in performance on any other parameters between the coated and uncoated heat exchanger.

Anti-ice validation and demonstration on finned heat exchanger

A small-scale validation setup and a full-scale LuVe unit (F30HC 611N7) were made and tested in the project. For the small-scale setup, several coatings were tested in validation experiments. The results from these small-scale tests showed that fins with a micro-nanostructured surface coated with a monolayer performed better than the other coated fins with regard to ice formation limitation. Therefore, it was decided to produce a large-scale unit with this coating and perform demonstration tests on such a unit. Comparisons were made regarding the results of an uncoated reference unit.

The experimental demonstration tests were conducted in a calorimetric room that had an air handling system inside, so the temperature and relative humidity could remain constant; an inverter system also helps maintain a constant pressure (temperature) evaporation during the frosting test.

The comparison between the coated and the uncoated unit was performed according to 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. The results showed a reduced frost formation when nano-structured fins, assembled on a complete unit (aero-evaporator), were used, reaching values of approximately 18%. This result is in line with the results from the validation tests made on the same type of fins but in a much smaller system (-17%).

4.1.3.2 Surface induced refrigerant fluid phase changes

Development of new surfaces

When improving heat exchanger efficiencies of evaporators and condensers, it is important to look at how the boiling behaviour of these systems can be optimized in order to give a decreased energy consumption. Looking at the schematic of the heat exchanger system (see Figure 16), where the coolant is evaporated on the left hand side and condensed again on the right hand side, the efficiency (ϵ) is very dependent on the difference between the evaporation temperature (T_0) and the condensation temperature (T_c).

As illustrated in Figure 16, the evaporation process in the evaporator of an air-conditioning unit or a heat pump occurs as flow boiling due to the presence of forced convection. Boiling in the absence of forced convection (known as pool boiling) can serve as a model to comprehensively illustrate the correlation between the surface superheat (known as the wall superheat and denominated ΔT) and the heat flux as flow boiling and pool boiling show comparable effects.

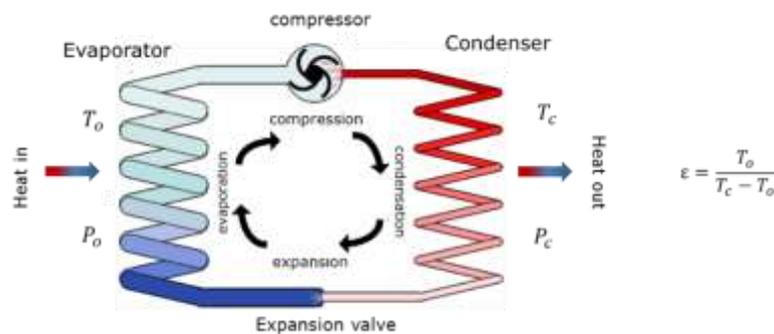


Figure 16: Schematic of a heat exchanger system.

Increasing the evaporation temperature is a very viable approach to maximize the efficiency of the heat exchanger system. An increase in evaporation temperature can be achieved if the boiling efficiency is enhanced.

The evaporation temperature is dependent on the flux transferred through the heat exchanger surface and the heat transfer coefficient, thus $q = \alpha (T_{\text{surface}} - T_0)$, where q is the flux, α the heat transfer coefficient, T_{surface} the temperature of the heat exchanger surface, and T_0 the evaporation temperature. The difference between the wall and coolant temperature ($T_{\text{surface}} - T_0$) is known as the wall superheat and is denominated ΔT . The heat flow rate per area (i.e. Q/A) is known as the heat flux. To achieve a high heat transfer coefficient a surface that shows a high heat flow rate at small wall superheat values is needed.

A normal boiling curve for water in pool boiling takes the form as illustrated in Figure 17 (to the left), where the mechanisms of boiling can be separated into several regimes. In the early phase (low wall superheat, ΔT), only natural convection contributes to the heat transfer and only a small amount of heat is transferred across the surface. At a certain ΔT , bubbles start forming (A) and increasing ΔT leads to fully developed nucleate boiling (B). At a certain ΔT (C), a film of gas starts forming on the surface, and the critical heat flux (CHF) is reached, followed by a transition to fully developed film boiling (D).

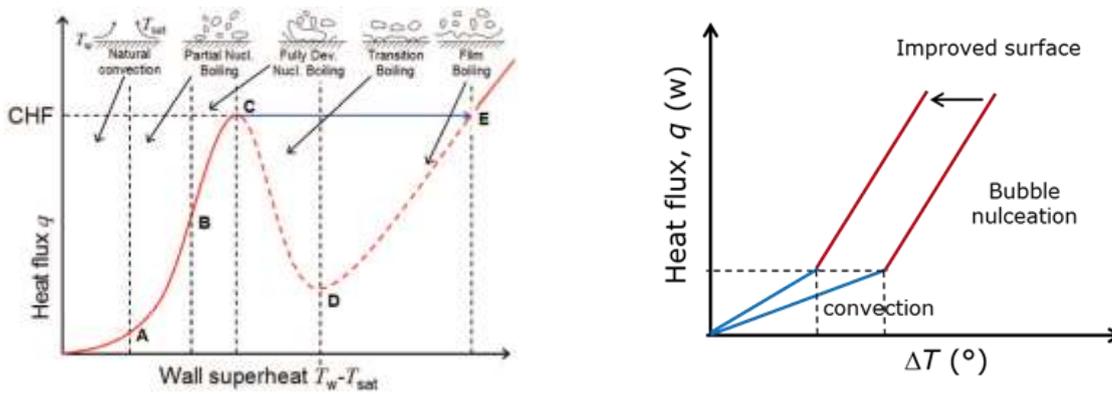


Figure 17: Left: Pool boiling regimes; Right: Effect of early onset of bubble nucleation

The regime that has the most effective heat transfer across the surface is the nucleate boiling regime. In order to create more efficient heat exchangers, surfaces with an earlier onset of bubble boiling can be developed, thus enabling a higher flux at a certain ΔT (see Figure 17 – to the right). Lately, a number of studies have been conducted in order to gain insight into and to control the pool boiling process by studying and modifying surface properties such as wettability, structure and surface chemistry, in order to predict and enhance the boiling heat transfer. Through these studies, it has been shown that wettability and microstructure are key parameters for optimizing boiling heat transfer. The majority of studies are performed using water as a cooling liquid. However, in this project we are interested in the natural refrigerants such as CO_2 and NH_3 .

In this project, the wettability of surfaces as well as the micro/nano-structuring of surfaces have been investigated to identify surfaces with improved heat transfer capabilities due to early onset of pool boiling.

Nanostructured surfaces

Almost all surfaces contain some amount of defects that can trap gas. These defects act as nucleation sites for bubble boiling. By structuring a surface in the nanometer range, it is possible to introduce these nucleation sites on the surface. By tailoring these for the liquid in question, the boiling efficiency of the liquid (refrigerant) on the surface will be increased, and the change from convective boiling to nucleate boiling can be obtained at lower differences between surface and refrigerant temperatures.

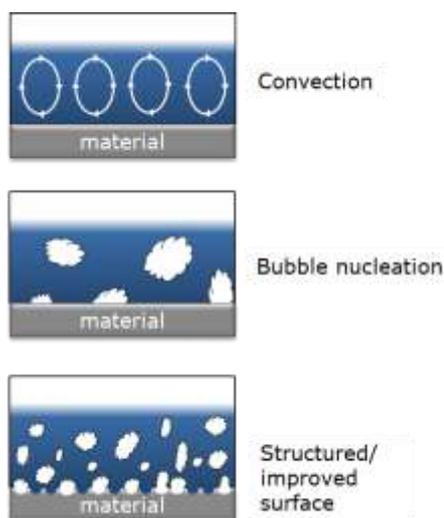


Figure 18: Structuring the heat exchanger surfaces is thought to have an effect on bubble nucleation

Structured surfaces with feature sizes in the 350-1000 nanometer (nm) range were produced at DTI. The structuring was based on a technique called colloidal lithography (see Figure 19). Nanosized polymer beads were deposited on a surface either by spray coating (known from spray painting) or by using electrode position.

Subsequently, an extremely thin layer of a very hard material called titanium dioxide (TiO_2) was deposited on top of the polymer beads. The layer was so thin that the polymer beads protruded from the layer and it was possible to remove the particles. After removing the particles, there were holes in the titanium dioxide film where the particles used to be. The size of the holes depend on the size of the polymer beads used.

Initially, small samples were made with 350 nm, 500 nm, 600 nm, 800 nm and 1000 nm feature sizes. The small samples were tested in a laboratory setup to evaluate whether the structured surfaces improved the heat transfer from the surface to the refrigerants compared to an unstructured surface (Figure 20). For both ammonia and CO₂, the structured surface with 500 nm features showed a significant increase in the heat transfer, as seen in Figure 20. Thus, the colloidal lithography technique was scaled up, and large heat exchanger plates with a diameter of 30 cm were structured at DTI and two plate-shell heat exchangers were assembled from the structured plates at Vahterus.

The performance of one heat exchanger was evaluated with CO₂ and the other with ammonia as the refrigerant. In the relevant temperature range, the nanostructured heat exchanger tested with ammonia showed an improvement in the overall heat transfer coefficient of 8% compared to an unstructured heat exchanger. Additional long-term tests showed fairly constant performance and the performance of the heat exchanger was basically unchanged after 58 days of long-term testing.

Surprisingly, no improvement was observed for the nanostructured heat exchanger tested with CO₂. It has not been possible to find a reason for the poor performance of the full-scale nanostructured heat exchanger used with CO₂.

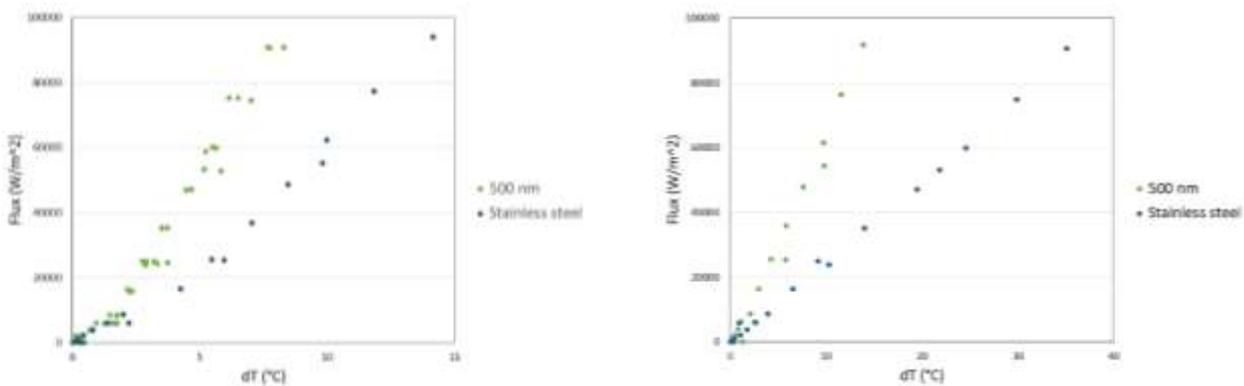


Figure 20: Results from small scale testing of structured surface with 500 nm features. The graphs show the heat flux as a function of ΔT in CO₂ (left) and ammonia (right) for the structured surface (green) compared to an unstructured stainless steel surface.

Sol-gel coatings

By applying sol-gel coatings tailored towards hydrophobicity (repelling water) or hydrophilicity (tend to be wetted by water), early onset of nucleate boiling was expected to occur. The sol-gel

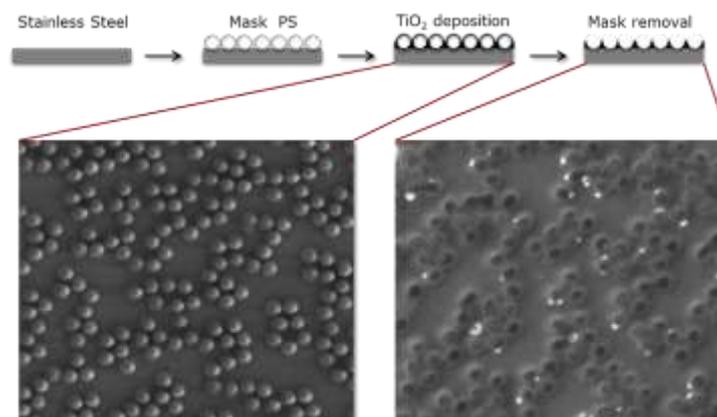


Figure 19: illustration of the principle behind colloidal lithography (top) and images of structured surfaces (bottom)

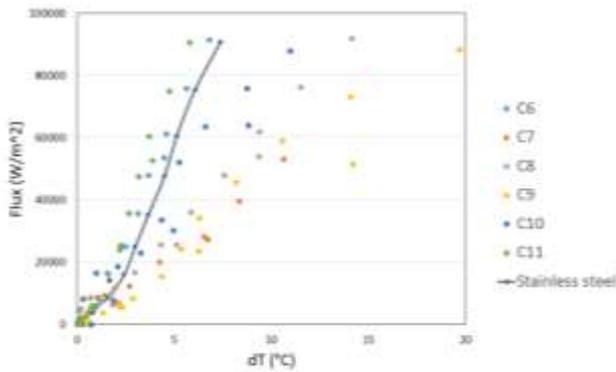


Figure 21: Results from small scale testing of selected sol-gel coated surfaces in CO₂ compared to an uncoated stainless steel surface

process is a chemical synthesis technique for preparing coatings, gels, glasses and ceramic powders. Compared to the other surface modification techniques, the sol-gel is a simple, economic and effective method to produce high quality coatings. In addition, sol-gel has several advantages including low cost, high adherence to the surface, chemical stability, film uniformity and low sintering temperature. The sol-gel process involves hydrolysis and condensation reactions of metal alkoxides or organosilanes and optional organic precursors to give gels. These can be tailored with properties ranging from hard, brittle and solely inorganic coatings to more

flexible inorganic organic hybrid coatings.

Several sol-gel recipes and post treatments were developed and the wettability of the resulting coatings was evaluated. It was possible to produce both highly hydrophobic and highly hydrophilic coatings. The heat transfer capabilities of small surfaces with the different sol-gel coatings were evaluated in the laboratory. Examples of the results are shown in Figure 21 with CO₂ as the refrigerant. Only coating C6 (very hydrophilic) and coating C11 (very hydrophobic) showed slightly improved performance compared to the uncoated stainless steel surface. None of the coatings showed improved performance in ammonia.

The sol-gel application process was scaled up to be able to cope with larger heat exchanger plates, and two heat exchangers with sol-gel coatings were produced. The performance of the coated heat exchangers was evaluated. The sol-gel coated heat exchanger tested in ammonia showed no improvements. This was not overly surprising given the small-scale test, and during the project it has been concluded that the sol-gel coating is degraded by NH₃. The sol-gel coated heat exchanger tested in CO₂ did not show any improvement either. Therefore, no long-term validation tests were performed with sol-gel surfaces for improved heat transfer.

Nanoparticle doped refrigerants

The potential of doping refrigerants with nanoparticles to increase the heat transfer from a heat exchanger surface to the refrigerant has been investigated. Nanodiamonds - diamond particles with diameters on the scale of 4-5 nanometers (nm) - were selected as the nanoparticles for the experiments, as diamond materials exhibit the highest known thermal conductivity of all materials and promising results for the use of nanodiamonds in refrigerant/oil mixtures had previously been reported in the literature. A prerequisite for using the nanodiamonds, or any other nanoparticles for that matter as dopant in the refrigerants, is to have the nanodiamond particles optimized to mix and interact well with the refrigerant liquid. The mixing and interaction is determined by the chemistry of the refrigerant and the surface chemistry of the nanodiamonds. Furthermore, it is of key importance to avoid that the particles form aggregates (clusters of several nanodiamonds) as this will impair the solution performance.

The refrigerants used in the project were liquid ammonia (NH₃) and liquid carbon dioxide (CO₂). These refrigerants were selected, as they are known to be “green” refrigerants with a limited environmental impact unlike the conventional refrigerants that are on the list of unwanted greenhouse gases.

During the project, Carbodeon has used their proprietary nanodiamond surface conversion technologies to re-functionalize the outer surface of nanodiamonds with carboxylic acid groups, hydrogen termination or amino-functionalization. The hydrogen terminated nanodiamonds were expected to have a high dispersion stability (i.e., do not form agglomerates) in liquid CO₂. Carboxylic acid functionalized nanodiamonds particles were predicted to exhibit high affinity (i.e., good mixing and interaction) to liquid ammonia based refrigerants. All nanodiamonds were produced as water-based suspensions.

Technical problems arose during the tests of nanodiamond doped CO₂. Adding a water based nanodiamond dispersion to liquid CO₂ posed a problem due to the low temperature of the liquid CO₂ (approximately -5°C to -10°C). Adding water based suspensions to CO₂ resulted in instant water ice formation and hence the suspensions obtained from Carbodeon could not be used in the CO₂ tests. Instead, tests were performed to get nanodiamonds dispersed in ethanol and then add the dispersion to the test setup. This circumvented the icing problems, but to get the desired nanodiamond concentration in the CO₂ it was necessary to add large amounts of ethanol based dispersions. The test results showed that the addition of nanodiamonds did not increase the heat transfer capability.

Technical problems also arose during the tests of nanodiamond doped ammonia. Adding water to ammonia results in a very alkaline environment, which corrodes parts of the test setup. To avoid adding water to the test cell, experiments of eliminating the water from the nanodiamond suspensions, while retaining the small particle size, were performed. The technique chosen was freeze-drying of the water-based suspensions. Using this technique, it was possible to get a fine nanodiamond powder with only limited agglomeration. The ability to suspend the freeze-dried nanodiamonds in liquid ammonia was tested. It was possible to suspend the freeze-dried Carboxylic acid functionalized nanodiamonds in ammonia and tests were performed. Unfortunately, no improvement in the heat transfer capability of the doped ammonia compared to the undoped ammonia was observed.

Due to the lack of promising results from the laboratory test, large-scale validation and demonstration tests were not performed on the nanoparticle doped refrigerants in the project.

4.1.3.3 Nanofluid development

The objective of this work was to develop nanofluids to improve the heat transfer over heat exchanging surfaces. Nanofluids are nanoscale colloidal suspensions containing condensed nanomaterial in a fluid. Nanofluids could improve the performance of the global HVAC system, but nanofluids are not currently used in commercial HVAC systems.

For the EnE-HVAC project, three kinds of materials were selected for nanofluid formulations:

- Nanoparticle based nanofluids
- Ionic liquid (IL) based nanofluids
- Phase Change Material (PCM) based nanofluids

With regard to the fluid phase, two different coolants were selected:

- Water
- A mixture of water and ethylene glycol

Nanoparticle based nanofluid syntheses

Nanoparticles are particles with a size ranging from 1 - 100 nm. Three different types of nanoparticles were selected: nanodiamonds, metallic nanoparticles and metal oxide nanoparticles.

The main objective was to increase the thermal properties (thermal diffusivity and thermal conductivity) of the original brine, but without changing the viscosity. The viscosity is related to the pump ability; when the viscosity is higher it is very difficult to pump and that will affect the cost of the final system.

Carbon-based nanoparticle dispersion

Dispersions based on nanodiamonds (ND) have been synthesized by the project partner Carbodeon, using NP chemical functionalization to obtain stable dispersion at different concentrations.

Dispersion stability over time has been monitored using two complementary techniques known as UV-Vis and zeta potential measurements. UV-Vis measurements were proposed because each NP has a characteristic absorption peak in this spectral range, which it is useful not only to control dispersion stability over time, but with a previous calibration, it can be used as a quantification technique to determine the NP content in the fluid. Zeta potential measurements were proposed because they are a standardized technique used to assess the nanoparticle suspension stability.

Once the method to assess dispersion stability had been set up and the ND based brine had been characterized, thermal conductivity was measured. Only one of the tested ND based nanofluids showed enhanced thermal conductivity of the host fluid compared to the pure fluid. Other physical properties (viscosity, density, heat capacity and diffusivity) were evaluated.

The main conclusions of the work carried out with NDs are:

- Nanodiamond dispersions obtained by chemical surface modification are stable
- Over time, dispersion stability can be monitored by ultraviolet-visible spectrophotometry (UV-Vis)
- Zeta potential is a useful technique to monitor particle size and dispersion stability, but only if water is the host fluid
- The thermal conductivity of the dispersions depend on the ND type

- The physical properties (viscosity and density) hardly change with the ND

Metal and metal oxide type nanoparticle dispersion

These nanoparticle dispersions were made using a “2-step” technique (i.e., the nanoparticles are added into the host fluid rather than created inside the host fluid). In this part of the study, the NP dispersion parameters were studied and optimized, working with two strategies:

- Surfactant addition
- pH modification

Both proposed strategies were optimized working with water as the host fluid.

The main conclusions of the work carried out with this type of NP are:

- Stable dispersions can be obtained by two different 2-step techniques: surfactant addition and pH modification
- Surfactants have a negative influence on the thermal conductivity
- Metallic NP in water generate an enhancement of the thermal conductivity
- Metallic oxide NP in water decrease the thermal conductivity of water, but they increase the thermal diffusivity

Based on the laboratory test results, three types of nanoparticle based nanofluids were selected for testing in larger scale at the test bench at DTI. These were:

- ND in Water
- Metallic NP in Water
- Metal oxide NP in water

The selected nanoparticles were tested in a test rig, which contains the same components as a full-scale system, but the test rig is built in a size (approximately 10L brine) that is usable in a laboratory. The water containing 0.01% nanodiamonds showed a tendency towards a small improvement compared to the pure water, but the improvement was low and in the same order as the uncertainty of the measurements. The metallic nanoparticles and the metal oxide nanoparticles did not show any significant improvement. Due to the lack of promising results from the test rig, no long-term demonstration campaigns were performed with the nanoparticle based nanofluids.

Nanofluids based on Ionic Liquids

An ionic liquid (IL) is a salt that is liquid at room temperature: ILs have interesting thermal properties and are becoming interesting in the field of formulated advanced coolants. In this case, the selected host fluid to work with was a mixture of water and ethylene glycol. The IL was selected according to the chemical structure (anion and cation), the thermal properties at high and low temperatures, and the solubility in the host fluid. 11 different commercially available ILs were selected.

Nanofluids were prepared from the preselected IL and some critical physical properties were measured, such as fluid pump ability linked with fluid viscosity and density; thermal properties, such as liquid operating range, thermal conductivity and viscosity, and corrosion capability. Ionic liquids are salts formed by anions and cations and therefore they pose inherent corrosion risks. Therefore, it is important to assess the potential corrosion risks before proposing an Ionic liquid as additive for use in an HVAC system.

For the validation of the performance of new coolants, it was proposed to use one specific ionic liquid in combination with stainless steel or aluminium surfaces. The selected IL does not show a strong

tendency to attack copper, but for safety reasons it was proposed to avoid copper in any part of the testing system. With this IL, nanofluids with different IL content were prepared and physico-chemical properties were measured. The positive effect of this Ionic liquid seemed to be more effective at lower concentrations.

Two IL based nanofluids were selected to test in the test rig. Both consisted of the selected IL in a fixed water and ethylene glycol mixture but with different IL concentrations: 0.1% and 1%. No significant improvement was observed for the ionic liquid based nanofluids. Due to the lack of promising results from the test rig, no long-term demonstration campaigns were performed with the ionic liquid based nanofluids.

Nanofluids based on phase change materials

Phase Change Material (PCM) is a substance with a high heat of fusion that during melting and solidifying (changing from one phase to another) at certain temperatures is capable of storing or releasing large amounts of thermal energy. The final aim of this activity was to obtain encapsulated PCMs to be dispersed in a host fluid (slurry) and obtain enhanced thermal properties. Encapsulation of PCMs is a useful approach to use PCM in direct contact with a fluid while avoiding PCM aggregation during the phase transition. In the framework of this project, the objective focused on encapsulation of PCMs.

The expected role of PCMs is to increase the heat capacity of coolants (water/ethylene glycol) during refrigerant phase transitions (from liquid to gas) and promote more effective processes because PCMs release energy during the phase transition from liquid to solid. The selected process is cooling in a heat pump.

As some encapsulated PCMs are commercially available, it was decided to start working with commercially available materials, consisting of organic PCM encapsulated in an inorganic shell. Materials were selected and characterized to verify thermal stability and the melting temperatures in order to assure that the phase transitions are in the working range of the coolant in the evaporator. Compatibility of commercially encapsulated PCMs with the selected coolant (water) were tested in order to assure that the PCM remains inside the capsule when it is put in contact with the coolant. The experimental results showed that the inorganic shell did not keep the PCM encapsulated and thus commercially encapsulated PCMs were not compatible with selected host fluid. Due to this behaviour, commercial encapsulated PCMs were discarded and efforts were focused on the sol-gel encapsulation strategy to produce silica microcapsules filled with PCM. The sol-gel technique was the selected encapsulation technique because of its simplicity, cheapness and high quality of the final products.

The main conclusions of the work carried out on PCM and encapsulation were:

- Commercial shells were not compatible with water and after mixing coolant with encapsulated PCMs, the PCMs migrate outside the porous shell, so commercially encapsulated PCM were discarded.
- A Sol gel technique was selected for laboratory encapsulation of commercial PCMs
 - Ternary diagrams were obtained by varying the microemulsion composition, and different points of the obtained diagram have been analysed with the aim to monitor the microemulsion stability and thermal properties. Selected compositions are stable over time, but thermal properties, such as thermal conductivity are lower than water, so the obtained microemulsion was not proposed as coolant.
 - Thermal characterization of microcapsules shows that the percentage of PCM inside the capsule depends on the strategy used - hydrolysis of the silica precursor occurs outside the microemulsion reactor providing an encapsulation rate around 50%.

- Characterization run by DSC shows a sub cooling process of the PCM (delay in the melting point). New melting points of encapsulated PCM are far from the defined temperature of the evaporator and might not be the best PCM for the application.

4.1.3.4 Modelling and simulations

For the simulation of phase change processes, the balance equations for mass, energy and momentum have to be considered. In this project, the phase change model of Juric and Tryggvason^{1[1]} was implemented into the commercial code CFD-ACE+ and used to simulate evaporation of liquid CO₂. The algorithm uses the operating pressure to calculate the local saturation temperature. As soon as saturation conditions are achieved at a computational cell, heat and mass of evaporation are calculated. For reasons of numerical stability, a certain threshold of evaporated mass has to be achieved before bubble formation starts.

The simulations were set up to correspond with experiments conducted at DTI and compared with the experimental results.

For the experiments, a test cell with a small chamber was constructed in which different liquids can be evaporated and condensed. The heat transfer and the temperature can be measured. Figure 22 shows a 3D- Model of this test-cell.

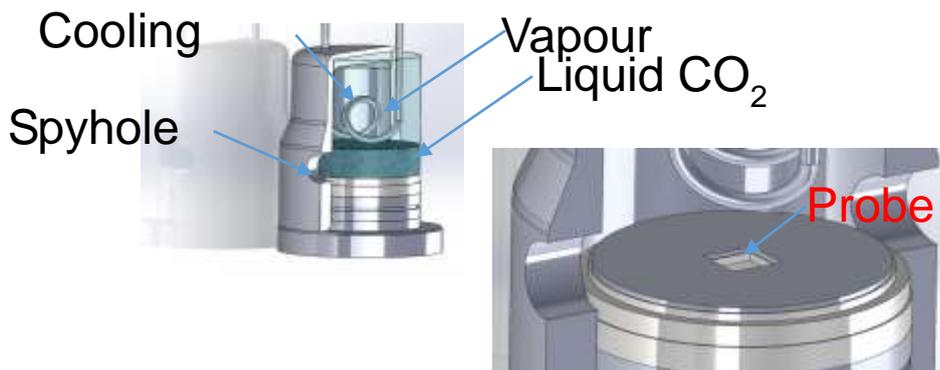


Figure 22: CAD model of test cell.

A computational model was created for this test cell with the meshing tools of CFD-ACE+. This model is only two-dimensional to reduce the needed computation time. However, for larger bubbles the shape is not symmetric and a three-dimensional model has to be used, if the shape of the bubbles is of interest. For the considered test cell, focus was on the overall heat transfer, and it is assumed that a two-dimensional model is sufficient for these simulations.

Test results with the phase change model turned on are shown in Figure 23. On the left, the heat source that is applied at the bottom of the probe hole is considerably small. In this case, no phase change occurs and the average temperature of the liquid increases linear in time. On the right side of the picture, a larger heat source was applied, leading to phase change and the formation of bubbles.

¹ D. Juric and G. Tryggvason: Computations of boiling flows, Int. J. Multiphase Flow, Vol. 24, No. 3, pp. 387-410, 1998

The average temperature rises at first, but drops when a bubble is formed due to the heat that is consumed for the evaporation. The sharp declines in the curve in Figure 22 correspond to the frequency of bubble release.

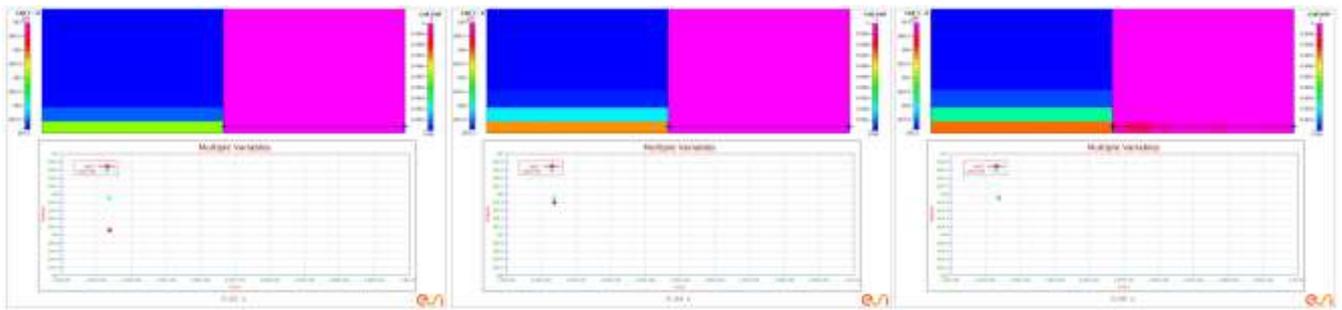


Figure 24: Picture sequence of start-up phase.

The correct calculation of saturation temperature is verified with the following picture sequence (Figure 25). The diagram shows the saturated liquid line for CO₂ as prescribed by the user. Depending on local pressure, the saturation temperature is calculated exactly as expected and shown by the calculated red dots along the saturated liquid line over time.

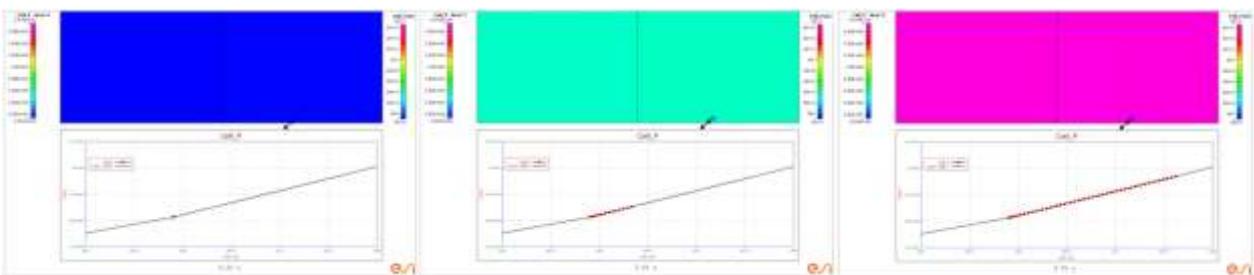


Figure 25: Picture sequence of saturation conditions.

For the 2D parameter study, the following heat fluxes have been simulated. In this simulation the bulk temperature is at -10°C. For low wall temperatures of -10, -9 and -8 °C no bubble formation occurs and only heat conduction and a slight natural convection leads to heat exchange at the heated wall. At -7°C bubble formation starts leading to an increased heat transfer coefficient. The slope of the curve indicates that the value of the heat transfer coefficient slightly fluctuates at an average value of about 5500 W/m²K.

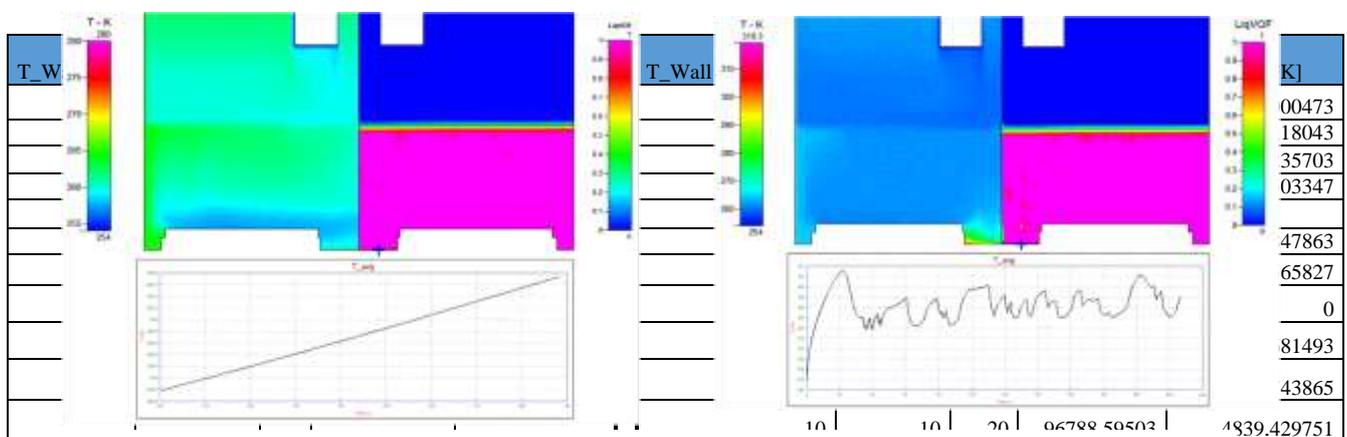


Figure 23: Heat transfer simulation in test-cell with small heat source (left) and large heat source (right)

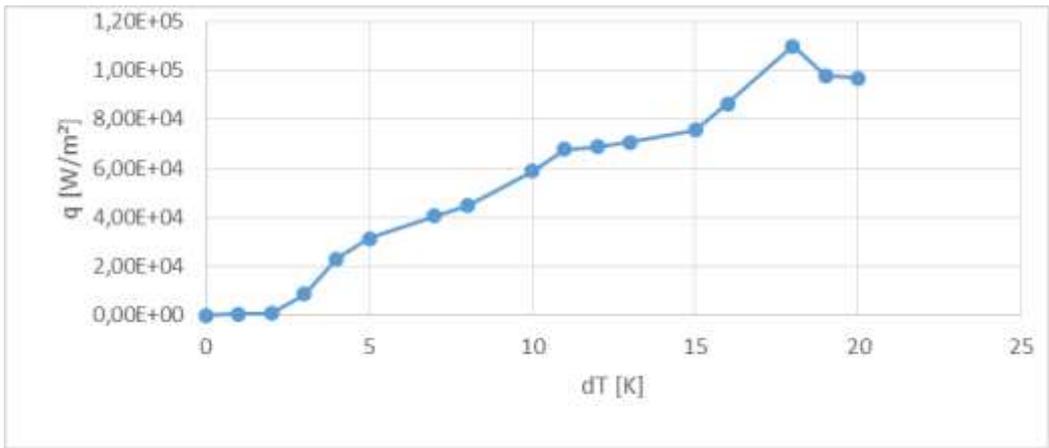


Figure 26: Total heat transfer over temperature difference.

Modelling of different surface structures / nucleation sites

As of now, different surface structures are considered by a time dependent probability of the numerical wall cells to act as a nucleation site. This factor between 0 and 1 needs empirical calibration to account for different surface structures. To the left in Figure 27, the nucleation probability is shown. Only cells directly at a nucleation wall have a probability greater than zero. To the right, the volume fraction of liquid CO₂ is shown and it appears that the formation of new bubbles happens only at nucleation cells. Figure 28 shows the influence of the number of nucleation sites on the total mass that has evaporated in the same amount of time. It appears that for a high number of nucleation points, more mass is evaporated. The total heat flux in both cases was 8444 W/m² and the time step size was 0.002 seconds. The evaporation starts shortly after 10000 time steps.

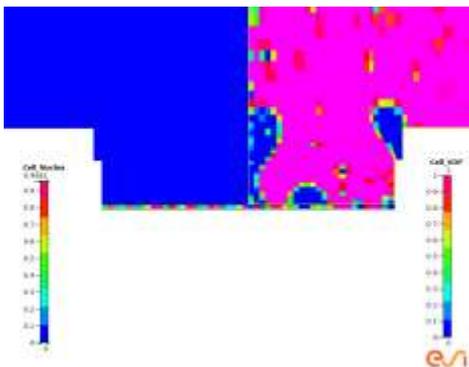


Figure 27: Nucleation site probability and bubble formation.

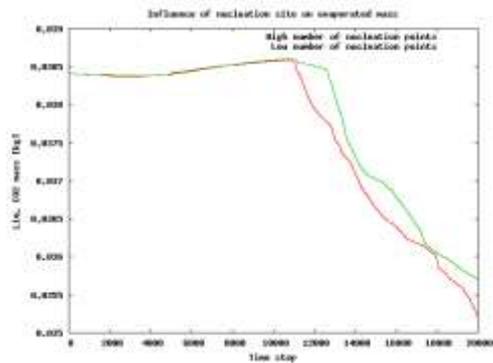


Figure 28: Mass decrease due to evaporation.

For a 3D model a parameter study of the DTI test cell for different wall temperatures has been pursued. Wall temperatures from -5°C up to +13°C have been tested. The difference in bubble formation was clearly visible and in good agreement with the experimental results.

Industrial scale heat exchanger

To study the effects in industrial scale, a simulation has been set up for a Vahterus heat exchanger. This heat exchanger will be part of the demonstration phase of the project.

Starting from the CAD model of the heat exchanger, a mesh was generated using the meshing tool VisCart. The mesh consists of approx. 48 million computational cells.

This model was then used to run a simulation of the flow and heat transfer in the heat exchanger. The runtime for this model is approx. 3 hours on 80 cpu cores.

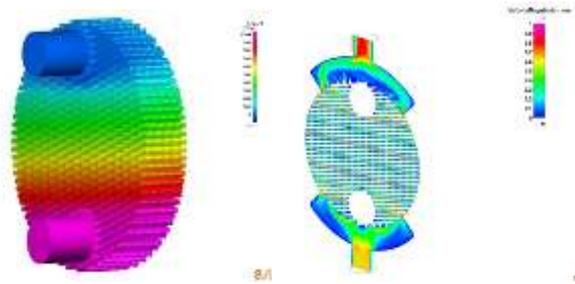


Figure 29: Pressure (left) and velocity (right) profiles in a plate heat exchanger.

Figure 29 shows pressure and velocity profiles obtained from the simulation. From these results, the main flow path through the heat exchanger as well as recirculation areas are identifiable. The flow field from this simulation can be used to calculate the conjugative heat transfer inside the heat exchanger.

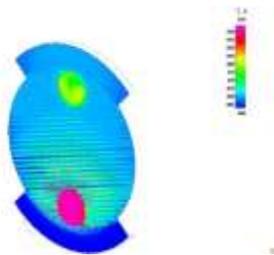


Figure 30: Temperature profile for plate heat exchanger.

Figure 30 shows the temperature distribution along a cut between the first two plates of the plate pack. A comparison between this simulation and experimental data regarding the total heat and the inlet and outlet temperature was part of the demonstration phase of the project.

4.1.4 The potential impact and the main dissemination activities and of results

Initially, several pathways for achieving energy savings in HVAC applications were envisaged:

- Nanostructured coatings including sol-gels and PVD coatings for increased heat transfer
- Nanotechnological coatings with anti-freezing properties to limit ice formation on heat exchanger surfaces
- Nanofluids for the improvement of heat transport

Two of these strategies have shown very promising results, namely the nanostructured surfaces for increased heat transfer and the nanotechnological coatings for anti-freezing properties; these are addressed separately below:

Nanostructured coatings for increased heat transfer

Development of nanostructured surfaces for increased heat transfer in heat exchangers using the fluid phase change refrigerants CO₂ and NH₃ have been demonstrated in lab-scale, however, it has only been possible to verify these effects in large scale for 500nm nanostructured TiO₂ surfaces using NH₃ as refrigerant. The tests run at Vahterus with low LMTD values indicate improvements of 15% in the evaporation heat transfer coefficient in the whole LMTD range. The durability of these surfaces have been further demonstrated in long-term tests at DTI.

For Vahterus, these improvements are very interesting, but the 15% improvements are not enough to implement a change of production, as a 15% increase can be achieved by scaling the size of the heat exchanger (number of heat exchanger plates), without increasing the size of the total heat exchanger assembly too much. These limited improvements compared to results obtained from laboratory experiments can be attributed to a lack of complete understanding of the flow and boiling regimes within Vahterus' heat exchangers. The use of nanostructured surfaces is expected to have an effect on the boiling heat transfer, but it is not completely known to what degree boiling heat transfer is dominating in a flow-system like the one used at Vahterus. These systems are expected to be a mixture between liquid film evaporation, boiling heat transfer and convection regimes, where the nanostructures will increase efficiency in the boiling heat transfer regime only.

However, development of nucleation boiling models at ESI can have a very large potential impact on the future design of heat exchangers from Vahterus, as these models can help improve the overall geometry of the heat exchanger plates in order to achieve significantly increased efficiencies.

However, the use of nanostructured surfaces for fluid phase-change heat exchangers does still have a large potential for specialized applications. Laboratory investigations have shown massively increased heat transfer efficiencies in systems dominated by boiling heat transfer. These effects can be implemented in non-flow systems, such as thermosiphons (heat pipes) used for cooling of, e.g., power electronics. In these applications, the predominant heat transfer will be through pool boiling, and size will be a very important factor, thus making these systems very relevant.

From this project, a very important secondary result with potential impacts has been the development of a very cost-effective nano-micro structuring technique that is scalable and enables the structuring of large industrial-scale systems.

Nanotechnological coatings for anti-freezing properties

Through this project, it has been demonstrated that developed sol-gel coatings can significantly increase the time it takes for ice to build up on an air heat exchanger. From the demonstration run at Exhausto on their complete heat exchanger set-up, the time before defrosting is necessary was increased from 5h 45' to 11h 30'. That increase is gained without changing the temperature efficiency of the coated heat exchangers. For further optimization a change of the de-icing flow should be considered, so the coated exchanger can become 100% de-iced before the unit returns to normal operation. Similarly, demonstrations carried out at LuVe S.p.A have revealed a reduction in the build-up of ice of 18% on their complete cooler systems using air-liquid cooling. In both demonstration cases, the frost formation on the heat exchangers was significantly different from non-coated heat exchangers, and it is evident that the frost spreading does not follow the normal patterns, and frozen droplets are observed instead of the more homogeneous frost layer that normally is observed.

The prolonged time before defrosting is necessary will result in a significant decrease in the energy used for de-icing, as, e.g., in a climate like the Danish, the number of periods with frost conditions that last longer than 10-12 hours (a night) is very limited compared to periods of 5-6 hours with frost conditions.

Already now, it is being discussed how and when this solution can be implemented in large scale, but there are still some obstacles that have to be overcome. For instance, the cost of producing the sol-gel coating, and the cost of the formulation of the sol-gel solutions for use in large-scale production. If this technology should be applied on a large scale, formulations based on other less toxic solvents will be preferred.

Nanofluids for improved heat transfer

Unfortunately, this approach did not yield the expected results. There have not been any significant positive effects of the use of nanodiamond-doped refrigerants, nor of the use of PCM materials or nanoparticles in brine systems.

However, a large knowledge base has been established by Tekniker and Carbodeon regarding the modification and use of nanoparticle systems. For Carbodeon, this means that they now have the tools for tailoring their nanodiamond systems for other applications. This will be used especially for enhanced polymer materials, where tailoring nanodiamond systems will significantly aid the integration of these into different polymer systems.

Although all aspects of this project have not resulted in solutions that will be implemented in heat exchanger products for the partners within the consortium, a large amount of valuable knowledge has been gained by all partners. Knowledge that will be used for generating new or improved products by the respective partners and possibly opening new business areas:

- For **Teknologisk Institut** and **Tekniker IK4**, knowledge gained in micro and nanostructuring of large complex surfaces is foreseen to be developed further and exploited within cooling applications and also transferred into other possible applications. The use of these surfaces have opened the possibility for highly efficient compact heat exchangers. For **Vahterus Oy**, this is a technology of great interest, but unfortunately the cost-to-performance of these technologies is still not at the desired level.
- The development of new sol-gel based coatings at **Teknologisk Institut** and **Tekniker IK4** has proven very successful, and this technology is expected to be brought to the market in cooperation with **LuVe SpA**, **Exhausto A/S** and **DVI** within a relatively short timeframe.

- Although the development of nanofluids for enhanced heat transfer was not successful within this project, the knowledge developed at **Carbodeon Oy**, **Teknologisk Institut** and **Tekniker IK4**, regarding synthesis and modification of nanodiamonds and encapsulated phase-changing materials for integration into cooling media, has matured the technologies significantly at the individual partners. That has given new possibilities for the use of these materials in other applications.
- For **ESI GmbH** and **ESI Software Germany GmbH**, new computer models incorporating nano and micro structure with boiling phenomena were developed. These models show great promise for use in prediction of boiling effects. Also, the tight collaboration between ESI and the involved heat exchanger producers have resulted in improved knowledge within these business areas for ESI, thus enhancing their competitive advantage. On the other hand, the involvement from the heat exchanger producers have opened up for a new understanding of their products, which enables them to improve their efficiency further.

Exploitation possibilities for the individual project results will depend on different factors, such as the degree of maturity of the specific result, the market situation of the sector where it can be introduced, the financial readiness of the partners trying to exploit the result etc.

Main dissemination activities

During the project period, the project partners have actively disseminated the project results through participation in seminars and conferences as well as publishing in trade magazines and for the scientific community. A dedicated work package was set up to manage the project dissemination activities.

To promote the project start-up and progress, a web-site was set up. It was set up with a public part for external dissemination and an internal part for internal information and file sharing. Furthermore, active promotion of the project and project results was actively disseminated during the project period through press releases and company websites.

As part of the dissemination of new innovative technological findings, the project partners have participated in international fairs and conferences. In the start-up phase of the project, we identified a list of conferences and fairs where it would be highly relevant to participate with dissemination purposes.

Through this project, new technologies have been developed, and to ensure the dissemination of this knowledge to both the scientific and technical community as well as to end-users, the publication of these results has taken place in publications aimed at both the industrial community and the scientific community.

Involvement with other EU initiatives

During the project period, the EnE-HVAC project has been involved in the nano-EeB cluster - later under the AMANAC CSA. **AMANAC-CSA** is a long-lasting collaboration and coordination platform aiming to maximize the impact of the participating Advanced Materials and Nanotechnology projects towards the European industry and society.

In this cluster, EnE-HVAC was initially partnered with other projects within the HVAC thematic area (EeB.NMP.2012-4 Nanotechnology based approaches to increase the performance of HVAC systems), namely nanoHVAC, nanoCOOL and EnE-HVAC. The main focus at the beginning of this cluster was to find possible synergies between the participating projects, and to increase the potential impact of the individual projects. The project activities changed and therefore we choose to join the insulation thematic area, as it has a lot in common with the EnE-HVAC project. For this cluster, the

main focus has been on sharing non-confidential knowledge between the participating projects and building databases on the data for use within the projects, but also for future projects within relevant areas. Apart from knowledge sharing, the projects within the insulation-HVAC thematic area have also supported the cross-dissemination of awareness of the different projects; therefore, initiatives such as links between project websites have been established on the relevant sites.

Secondly, the EnE-HVAC project was invited to participate in the “Engineering and Upscaling Cluster” with a start-up workshop in Brussels in February 2015. The focus on this cluster is how to overcome the barriers and obstacles for engineering and upscaling with regard to ensuring impact of the results produced through EU funded projects.