MULTI-DIMENSIONAL OPTIMIZATION OF A NEWLY DEVELOPED AIR TO WATER HEAT PUMP

Simon Klink, heat pump development, Bosch Thermotechnology, Lollar, Germany;
Max Meise, heat pump development, Bosch Thermotechnology, Lollar, Germany;
Tobias Geibel, head of heat pump engineering, Bosch Thermotechnology, Lollar, Germany;
Niklas Engholm, heat pump development, Bosch Thermotechnology, Tranas, Sweden;
Kjell Gustafsson, heat pump development, Bosch Thermotechnology, Tranas, Sweden;

Abstract: A new air-water heat pump has been developed by Bosch Thermotechnology with the goal of collectively satisfying customer, installer and newest legislative requirements. In a first step, a multi-dimensional noise, size, weight and heat transfer optimization study was performed to size the hardware components. This provided the foundations for a much better performing heat pump that was more compact and lighter compared to previous units. New materials and components, an intensive study on the fan, air chamber and evaporator optimizing noise, air flow and size lead to a significant improvement. In a second step, an optimized heat pump control algorithm was developed to maximize the inverter driven compressor capability in terms of efficiency and operating envelope by minimizing reliance on the electric heating rod and on/off cycling with a more continuous heat supply. Other key features include novel inverter cooling and full reversibility for cooling on warmer days showing the customer comfort being in focus. The contribution of all steps will produce a high European Ecolabel score and be very good compared to market level. This paper describes the optimization methodologies and their outcomes. Also described are the various thermodynamic, CFD numerical calculations along with measurements undertaken during development leading to the final design and results.

Key Words: Inverter; Control; Efficiency; Low noise; Air flow

1 INTRODUCTION

In the recent years heat pumps have come up more and more again in Europe. The main driver for this development is the increased need for energy efficiency, to safe heating energy, but also CO_2 substituting mainly direct electric heating, but also oil and gas fired burners. Heat pumps are especially beneficial for new built houses with low distribution temperatures as underfloor heating, but the share of usage in refurbished houses is rising. In former times the liquid water heat pump was dominating the European heat pump market. But with lower energy demand of old and new houses, the drilling costs are more and more dominant. Therefore the market is currently switching from a liquid-water market to an air-water market.
First air-water heat pumps were typically built with the knowledge and the spirit of liquid-water heat pumps. But today, fully optimized air to water heat pumps are required to fulfill the market needs. Therefore Bosch Thermotechnology has started the development of an entirely new air to water heat pump series with a completely new design.
The approach for this was first to collect all the requirements; from customers, installers, legal changes and internal needs (Chapter 2). From these requirements the design and the optimization could start, taking into account and looking into all relevant components, parts will be shown in chapter 3, where the refrigerant circuit and the controls system will be

discussed. A deeper insight will also be given in optimization of air flow and chassis structure during development. In chapter 4 the benefits of the measures taken will be shown.

2 CONDITIONS

One of the most important work packages in development is the collection of all demands for attributes and features of the new product. This process called requirements engineering is meant to involve all relevant parties like customers, installers, marketing, service, production and development.
The requirements then show very different views on a product: Customers want an efficient, easy-to-use system, the installer prefers easy handling and system integration, service requires reliability and quick maintenance, sales needs a good price/cost ratio, production wants a fabricable design and few parts, marketing requests Unique Sales Points (USPs) and nice design and development wants to build something really cool. At least the last one is easily done with a reversible heat pump.
Especially efficiency is a point where also the government puts some pressure on the design process: To reach a good value on the energy label is a strong requirement which also effects sales. The test conditions as described therefore e.g. in EN 14825 lead to changed development systematics: Previously, there had been a strong focus on single test points as described in EN14511, where COPs at certain relevant values had to be reached to be competitive on the market. Often advertisements were done with one single COP, for example at A7/W35.
Of course during development, heat pumps have not exclusively been optimized for the test points, but as in every case when a certain standardized test is used to judge performance, main attention lasts on these certain conditions. This is now changing to a look more on the operating situation as a whole and in combination with real life seasonal effects, represented by the SCOP, or the energy label in the end.
In addition to the involved stakeholders also political decisions have an influence on the requirements. The new F-Gas regulation for example sets a limit of 10 tons of CO_2 equivalent to the refrigerant filling amount for hermetically sealed refrigerant circuits. For R410A as used in this appliance, this results in a maximum charge of 4.8 kg. Even the largest unit of the new series stays below this amount.
After very first concept ideas in direction of low GWP refrigerants it was decided not to start with a development on natural refrigerants for this new series. Market acceptance is still quite small and legal issues regarding flammability not entirely clarified. However, it is clear that R410A will only be the preferred solution for the coming years. Later, additional variants are always an option.
In the end the customer satisfaction is most important: Performance, efficiency, sound, appearance and operation must be excellent, and all that at a competitive price.

3 OPTIMIZATION

Shifting the way of judging heat pump performance according to the relevant standards naturally also changed the development targets. The new standard (see 813/2013 and 811/2013: Space and combination heaters) shows much more relation to real application in a heated house compared to the former standard. Tests have to be done at part load conditions, which give a much better evaluation of how the machine will perform in a house. The heat pump needs to be able to reach high efficiencies at very different operating conditions.
The approach during development was multi-dimensional, the target was to include all aspects of the heat pump and find optimization potential on every level. The series was designed as a new platform from scratch, leaving many options to introduce new ideas and go new ways. New components with new control algorithm were introduced, which are each by each of high quality and optimized to best efficiency. Most of the components themselves

are fore sure already known on the market, but have been combined and optimized in one unit.

The following fields were identified during the project planning process as the ones showing most potential for optimization:

- Refrigerant circuit design including heat transfer and control algorithms
- Air flow and sound
- Casing and insulation
- System integration and user friendliness

3.1 Refrigerant circuit

Flexibility is one of the key words to describe the refrigerant circuits which were developed for this new heat pump series of five sizes with nominal heating capacities ranging from 5 to 17 kW. All machines are fully reversible and modulating, not only the twin rotary compressor, but also fan and primary pump. To make sure that high efficiencies can be reached in any operating condition, an elaborate, modularized control logic has been created to drive the two electronic expansion valves and the compressor in the best possible way. Compressor operation is permanently safeguarded as the control monitors speed, pressures and temperatures and keeps them in the limits given by the compressor envelope.
Correlations for thermodynamically relevant values based on refrigerant properties are used to predict the circuit behaviour, so the machine can adapt to changing operating situations very quickly. This feed-forward calculation enables for example presetting of the expansion valves in order to reach stable operation in significantly reduced time.
To optimize heat transfer, fin-and-tube evaporators with large area and optimized distribution and asymmetric brazed plate heat exchangers as condensers are used. The two valve design with a receiver tank in between makes it possible to actively shift shares of the refrigerant. Any reversing operation for defrost or when switching e.g. from cooling to domestic hot water (DHW) production and back can be done much smoother this way. It also gives the possibility to actively control subcooling in the condenser.

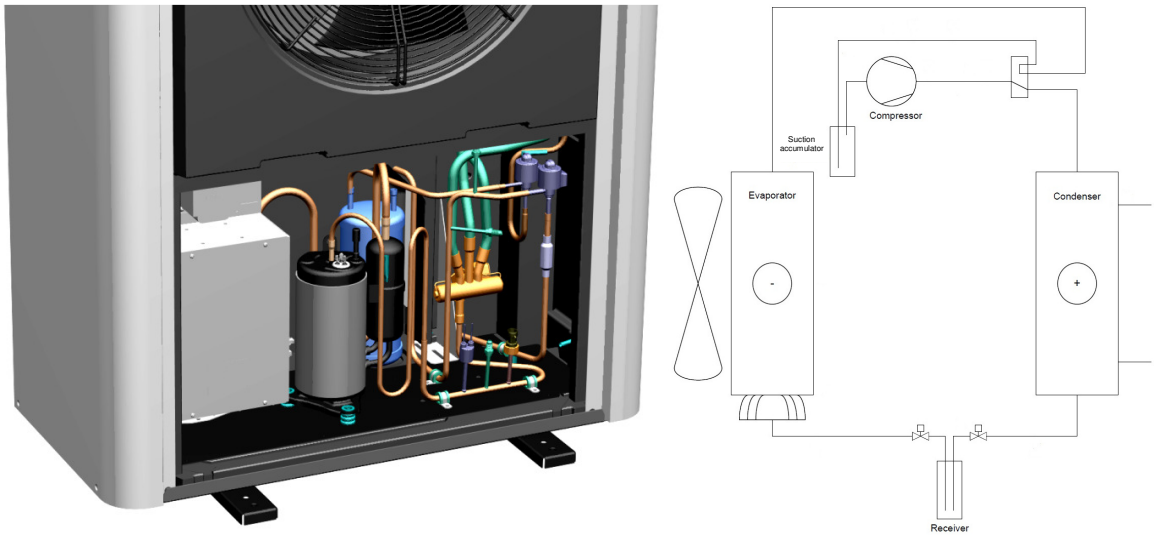


Figure 1: Reversible refrigerant circuit design of the new heat pump series (left) and schematic drawing of the refrigerant circuit with evaporator and modulated fan, rotary compressor with BLDC motor, electronic expansion valves, asymmetric brazed plate heat exchangers (right).

Defrosting is one of the main reasons for reduced efficiency of many air source heat pumps compared to brine/water applications. Utilizing natural saving options and controlling fan speed in an intelligent way, it was possible to reduce the need for defrosts in wide areas of

the operating range. At air temperatures above a certain threshold of for example 5 °C, the heat pump can even keep supplying heat or DHW even while defrosting.
The newly developed inverter solution is cooled by refrigerant, leading back the power electronics' losses into the refrigerant circuit after the evaporator. Most of the time, the latter can thereof be used much more efficient for evaporating only, superheat is taken care of afterwards. The temperature of the inverter can also be held low at high load conditions, for example during DHW production in summer. This increases component lifetime and reduces the risk of electronic failures, which is a sensitive topic for heat pumps in field.
The following diagram in Figure 2 visualizes the effects of low superheat operation and usage of inverter cooling by suction gas on efficiency and heating output. EES® (Engineering Equation Solver) was used for calculation, own measurement results are given for comparison.
Some operating situations like start-up or other transition modes require a higher suction superheat than usual to protect the compressor. In such modes, heating output rises with higher superheat due to the extra energy put in by the inverter. As evaporating pressure does not have to be reduced as usually done in such cases, the inverter cooling gives benefits for reachable condensing pressure. Otherwise, the rising discharge gas temperature would set a limit, resulting in reduced supply temperature capabilities.
The inverter cooling also improves efficiency for the mentioned operating modes with higher needed suction superheat.

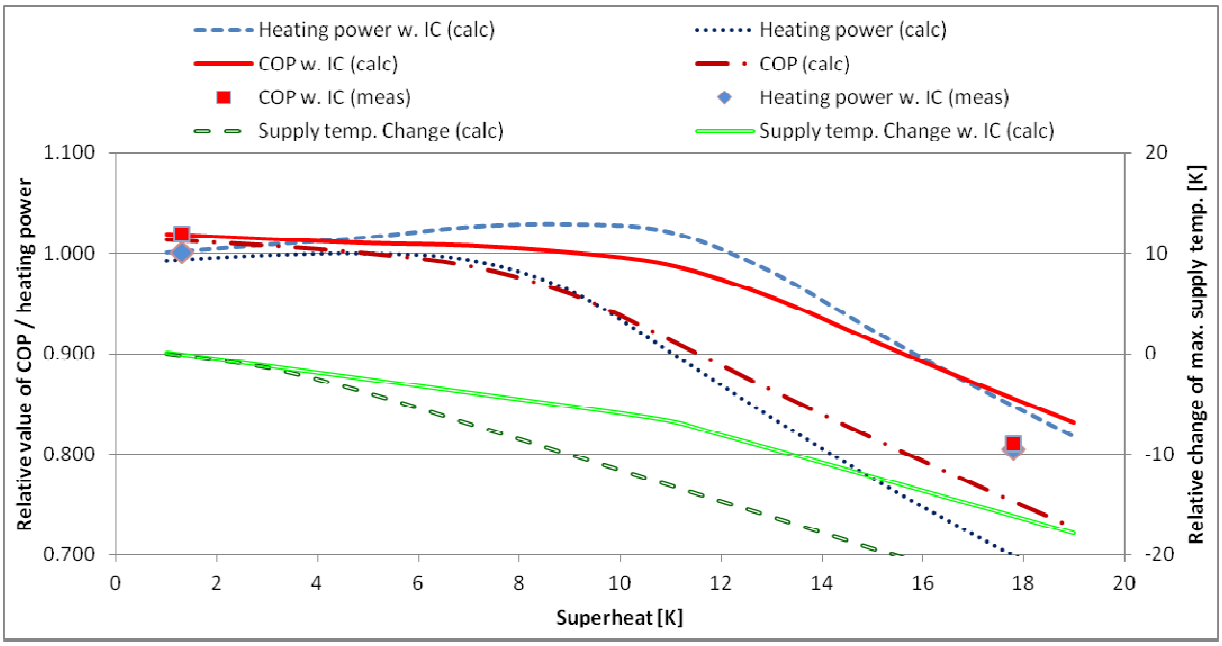


Figure 2: Effect of superheat on COP and heating power (left axis) and maximum supply temperature (right axis) with and without inverter cooling (IC) by the suction pipe.

Besides these control functions directly related to the refrigerant circuit operation, other features have been implemented. An optimized fault detection system in the heat pump control recognizes mistakes in the installation, e.g. wrong connection of water flow and return pipe and therefore gives an early warning to the installer at first start-up. Full-text error codes make it easy to find and remove failure causes quickly. In case of a leak, the control will detect the loss of refrigerant during operation by supervision of the refrigerant circuit operating parameters. Thereof, a correct failure description can directly be given to the service team, reducing service effort to a minimum.
The whole refrigerant circuit and also the chassis were developed and designed in a modularized approach, wherein functional sections were clearly defined with interfaces to the adjacent parts. Besides the advantages due to parallelization during development and in

production, this approach makes it easy to update certain modules re-combine or add functionalities without changing the main concept.

3.2 Air flow optimization

As an air to water heat pump takes the free energy out of outdoor air, a certain air flow needs to pass the evaporator. The less air flow, the larger the temperature drop of the air and the lower the evaporating temperature at given outdoor air conditions. But low evaporating temperatures have the potential to spoil the COP. A too high air flow puts cost on the fan, reduces efficiency due to the high fan power, and in the end makes a lot of noise. Therefore the air flow needs to be balanced to the heat pump power.
But moreover, as the evaporator takes a bigger portion of the heat pump cost, the total area of the evaporator need to be used to its optimum. A uniform airflow through the whole evaporator should be the target. As the different parallel refrigerant circuits of the evaporator are oriented vertically, this target can be split into two parts:

- The distribution of the airflow among the different parallel refrigerant circuits
- The airflow distribution over each refrigerant channel area

Thereof, the distribution among the different parallel refrigerant circuits is much more important compared to the latter one. As systems regulating the refrigerant flow for the different circuits are not yet established for reversible systems, the weakest circuit dominates the heat transfer of the complete evaporator. Therefore much attention was put on equalizing air flow among the different parts, the difference between circuit with most and least air flow never exceeds 20%.
To evaluate the uniformity of air flow, a CFD calculation was done, the results are shown in Figure 3. The uniformity of the air flow is shown to the right, where the corners have a little less air flow compared to the center. It also shows the location of the different channels of the evaporator.

Table 1 shows the results for the channel with minimum flow (typically part 7 of the evaporator, see Figure 3) indicating the power level of the evaporator for different air chamber sizes. It shows that with increasing the distance between evaporator and fan, the air flow of the least channel is increasing compared to the reference which is the average flow for the medium length. But the second step by enlarging by 100mm further, the effect is very little. The total air flow does not differ very much among the different variants. Therefore the medium length was chosen to be the final design.

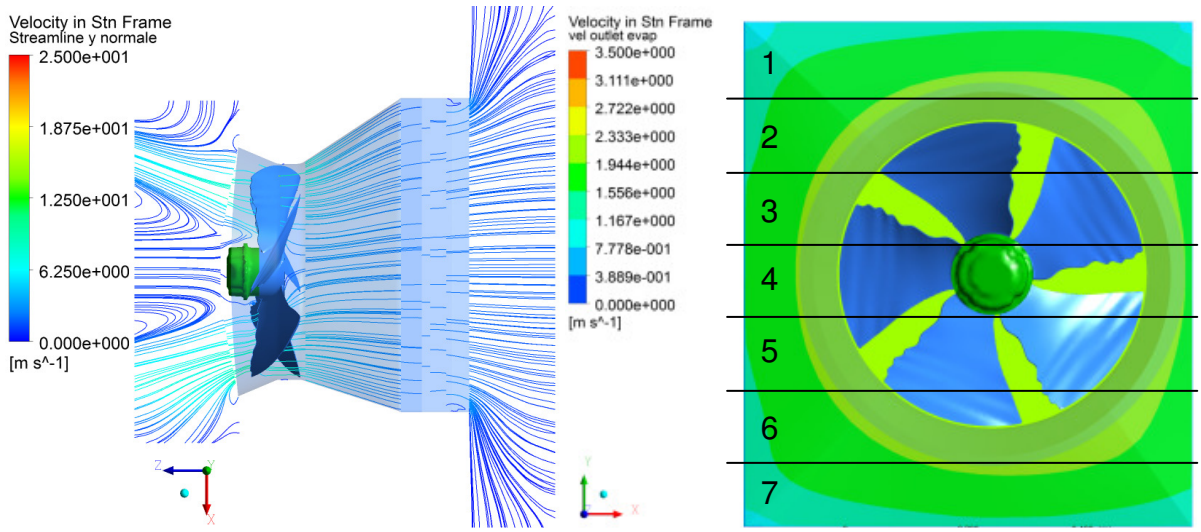


Figure 3: Streamline results of the air chamber CFD (left) and axial air velocity through the evaporator with indication for the different channels (right) for the final design.

Table 1: Air flow through the evaporator segments for different air chamber designs

Design	Minimum value (rel.)	Maximum value (rel)	Total value (rel.)
Final design -100 mm	0.79	1.10	0.98
Final design	0.87	1.06	1.00
Final design +100 mm	0.90	1.07	1.01

Sound power is a very important topic from end customer point of view which leads to many complaints all over Europe, from end customers themselves, but also from their neighbors. Due to this, sound power reduction is very important to safeguard the future of heat pumps. Therefore the evaporator has a large cross-sectional area to reduce the air speed at a constant air flow rate. Moreover a lot of attention was put on the selection of the fan to have lowest sound power within the pressure drop curve of the evaporators.
To set up the right fan speed for each operating condition to optimize the COP, all measurement data available within the heat pump is taken into account, such as compressor speed, air temperature, pressure levels and many more. To give the end customer further possibilities to reduce the sound power, a special silent mode was developed to give the end customer the choice between optimizing sound power and efficiency.

3.3 Lightweight chassis construction

For the construction of the chassis, we were mainly focussing on easy installation. Installers are used to easy installation for other heating devices since quite a while. A wall hung gas boiler needs to be lightweight anyway, and a one man lift is typical. For air to water heat pumps the need for a pallet truck is quite usual as they can easily exceed 200kg or even much more. Therefore the weight is very essential for easiness of installation. The target was to achieve a two man lift heat pump, so there is no need for extra equipment or accessibility of the place of installation.
To achieve a two man lift at least for the smaller sizes with 5 to 9 kW heating output, a completely new construction was necessary, as for the commonly used steel sheets or even square tubes this seems to be not reachable. A much lighter material is expanded polypropylene (EPP), known as insulation from other heating devices, but also from car bumpers, so a quite robust material as well. Compared to steel, EPP has the following advantages:

- Lightweight
- Insulating
- High sound and vibration damping
- Easy sculptured surfaces

All this together gives a high potential for a functional integration, so insulation of the refrigerant circuit is not necessary as all refrigerant parts are in a closed box of EPP, the EPP is fixation of the fan and air chamber at the same time.
On the other hand, the material is much weaker than steel, so it is more difficult to keep the weight of the parts. Therefore parts with a high density, such as compressor, plate heat exchangers or the inverter are placed in the bottom of the heat pump. To give a smaller footprint and to allow the water created during defrosts to be drained very easily, it was decided to place evaporator, air chamber and fan on top of the refrigerant circuit. But in this case, the EPP has to carry the weight, especially of the evaporator. The most critical cases are seen as

- High ice load of the evaporator, just before defrost
- High temperature of the EPP, summer
- Cold temperatures in combination with vibrations (transportation)

To ensure that the structure is capable to take the load in all conditions, the three extreme conditions were taken as a reference and the stress level was calculated beforehand by FEA. The calculations started with a validation of the material model by repetition of the material compression tests. By having a good agreement there, it is possible to calculate the stress level for the more complex geometry.

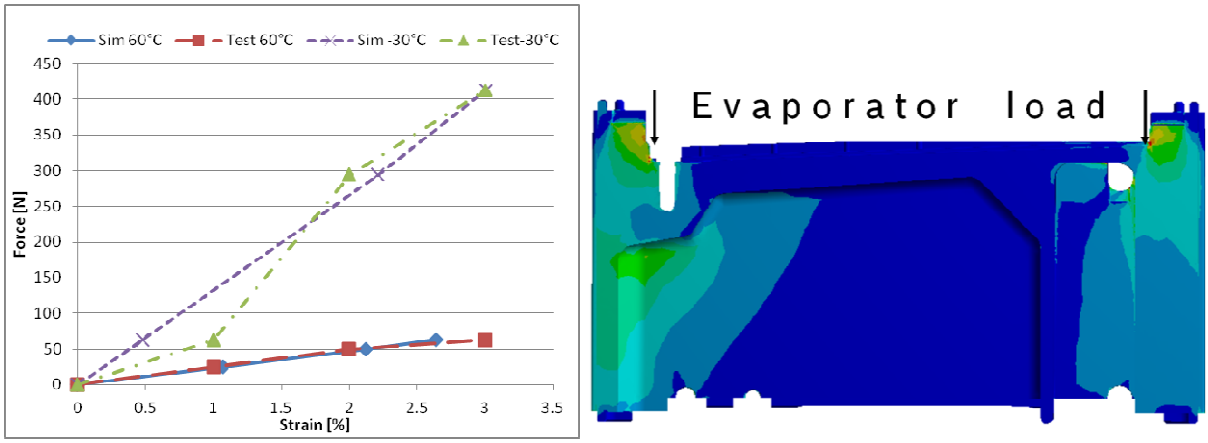


Figure 4: Material model validation by simple geometry tests (left) and strain contour plot for the part carrying the evaporator (right) with 2g acceleration

As material model, a neo-hookean model was used to take care of the high strain values that might occur. Nevertheless the interest is mainly in comparably small strain values as larges values should not occur anyway. Therefore test data from a block compression test was taken and compared to simulation data at both, extremely high and extremely low temperatures. The comparison is very good for the much more critical high temperature values (See figure Figure 4, left). With the values given a strain calculation can be performed on the different EPP parts, whereas the most interesting one is the one below the evaporator (Shown in Figure 4, right).

Table 2: Comparison of strain levels for different conditions in comparison to the material capability

Condition	Load	Strain [%]	Elastic strain limit [%]
-30°C transportation	2g	0.29	3.0
60°C transportation	2g	1.75	3.5

The load during transportation gives a dynamic acceleration of 1g (see Hapag-Lloyd), with additionally 1g static load, resulting in 2g total load. This load overcomes the other conditions like ice forming. So calculating the 2g load for different conditions safeguards the other conditions as well. In Table 2, the strain level for high and low temperature is given for the maximum applicable value of 2g acceleration. The strain level for -30°C is very low, almost negligible. The value for 60°C is significant, but still way below the elastic limit, giving a safety factor of 2.
By the calculations given, it is proven, that the light and insulating EPP structure withstands all mechanical loads.
As mentioned before also the chassis is split in modules, which can easily be disassembled at the installation for improved serviceability. The refrigerant circuit or the fan can be accessed by only removing very few screws to take the relevant cover plates and EPP chassis parts off.

3.4 System

Being a company with system focus, easy and efficient integration of the new heat pump series into a hydronic heating system concept was important from the start on. Combination with different buffers and cylinders and solar thermal as well as other heat sources like wood stoves or gas or oil boilers is possible without much effort. The system controller combines control demands from all parts of the heating system. Parallel operation of 2 heat pumps is already possible with the standard control, more units can be cascaded with an optional additional cascade module. Other available accessories are room controllers and modules for solar heating, additional heating circuits or pool heating.
Combined with a new indoor unit containing low energy circulation pump (LECP), electric back-up heater, expansion vessel, control and a stainless steel domestic hot water cylinder with a volume of 180 l (solar coil optional), the new heat pump already integrates many system components. Special attention was paid to the newly developed DHW cylinder with integrated coil, optional also one for a solar thermal system and improved EPP insulation, which is optimized for low heat losses.
Many features make life easier during installation or in case of service needs. One of them is a diagnosis function, which gives the status of all components whenever requested.



Figure 1: Tower indoor unit of the new heat pump series

Alternatively, the heat pump can be combined with an indoor box to use an external cylinder or to combine it with a second heat source. As the controller operates via EMS bus protocol, for example a gas condensing boiler can be operated fully modulating in combination with the heat pump.
To ensure maximum system efficiency, the second heat source is used especially at very low outdoor temperatures, bivalent operation therefore controlled by a hybrid algorithm either focusing on maximum efficiency or lowest energy costs, depending on tariffs of electrical energy or e.g. gas as set by the customer.

For this algorithm, the control is able to calculate current heating output and COP. This makes it possible to switch, whenever the efficiency of the heat pump falls below that of e.g. a gas condensing boiler in terms of primary energy use.
The user interface is now based on a new system controller which will be used for the whole portfolio of upcoming products. For the installer it is thereof easy to change settings in the well-known menu structure. For the end customer, the clear design and intuitive operation give easy access to important functions and parameters, too.
Also smart grid functionality is given, either by a robust wired solution as preferred for example on the German market or via internet protocol. The optionally available IP module allows the customer also to access his heat pump via smart phone to e.g. set a program while being on vacation or to control heating or DHW functions from any place in the house or garden.
Also integration of the device itself was considered. It is not necessary to hide the machine, as it was designed to meet also visual aspects. It is not needed to put it far away from the house, as it operates quiet. And there has not much effort to be taken in preparing a stand or base plate, as the heat pump is lightweight and comes with feet already attached, with which it can be mounted e.g. on paving slabs. The ground clearance of the fan makes it possible to place the unit directly on ground level in regions where snow heights stay below 40 cm.

4 RESULTS

All improvements, calculations and optimizations shown in chapter 3 should result in benefits for the end customer, the installer or environment. Therefore a comparison to other existing heat pumps is very important. **Error! Reference source not found.** shows the improvements made in an impressive way. The comparison is undertaken for the previous product, but for competitor products as well. For COP an improvement of 35% compared to the previous product was achieved. This will give the end customer a reduction of energy bill of 26%, and the same percentage to the CO_2 emissions. This was mainly possible due to the intelligent control of the refrigerant circuit with optimized subcooling and superheat, the inverter losses fed back to the refrigerant circuit and a well balanced utilization of the complete evaporator area.

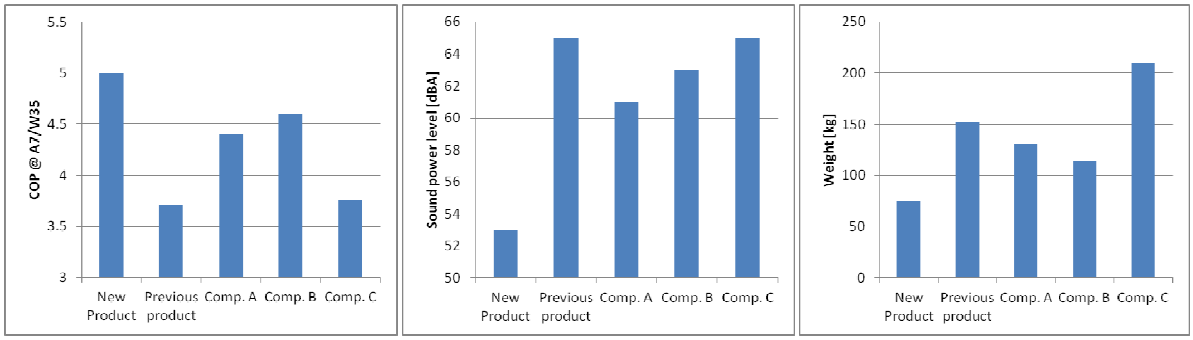


Figure 5: Comparison of the new developed product to already existing products in terms of COP (left), Sound power (middle) and weight (right)

The sound power level could be reduced by 12 dB(A) which equals a reduction of 94% and gives a massive benefit to the end customer, especially in suburbs with high density in houses where neighbors could complain when the heat pump is noisier. The main focus was to select the right fan for the pressure drop curve of the evaporator, to have a large evaporator and a large fan diameter to achieve small air speeds and to have a high damping on chassis and housing of the heat pump.
In terms of weight of the outdoor unit big steps were undertaken to reduce the weight significantly, 75kg were reached for the smaller capacity sizes which is less than half of the previous product. But also for the larger sizes, the weight could almost be halved, and also compared to other heat pumps in the market, the weight is very low. This makes it much

easier for the installer. The main part of this improvement was achieved by introducing the foam EPP as a structure, incorporating many other functions.
Overall the heat pump shows a very good balance between customer needs, installer needs, new legal requirements and boundary conditions. The main topics such as ease of installation, sound level, system integration, but pretty much the efficiency to reduce cost for the end customer and to protect the environment are achieved.



Figure 6: Outside view of the new designed heat pump series

5 SUMMARY

As described in the introduction, the approach in this project was to consider the needs of end customers and installers first. This was completed by requirements raising from changing economical and legal conditions, paying attention to the broad variety of target markets from northern Scandinavia to the shores of the Mediterranean sea.
For the aim of multi-dimensional optimization, efforts were taken in various directions, including simulation on component and system level and extensive test work of the appliance during all stages of development. Of course trade-offs are necessary to e.g. reach a high performance while keeping the economical and dimensional limitations for the heat exchanger sizes in mind.
Proper research was conducted to analyze and describe relationships of operating parameters of the refrigerant circuit and many other components of the heat pump, leading to a thorough understanding of dependencies. This made it possible to tweak design parameters of e.g. the air chamber to maximum extend and create optimized control correlations.
All these steps together resulted in an entirely new and improved heat pump concept. Key functions were thought new, resulting in improved operating performance and usability. Easy installation and high efficiency reduce costs both at the start and over the complete lifetime of the appliance. An improved design and low noise increase customer's quality of life and neighbor's contentment.
The new machine is just now introduced to the European market.

6 REFERENCES

Hapag-Lloyd (2010). “Container packaging”, http://www.hapag-lloyd.de/downloads/press_and_media/publications/Brochure_Container_Packing_en.pdf [Accessed Jan. 26, 2014]

EES “Engineering Equation Solver”, http://www.fchart.com/ [Accessed Jan. 26, 2014]

European Council for an Energy Efficient Economy (ECEEE). “813/2013 and 811/2013: Space and combination heaters”, http://www.eceee.org/ecodesign/products/boilers [Accessed Jan. 26, 2014]