End report 346 - 036

NOVEL
SPIRALSHAPED COUNTER FLOW HEAT EXCHANGER FOR DECENTRAL VENTILATION

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SUSTAIN SOLUTIONS

DTU Elektro
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Foreword

Project '346-036 Novel spiral shaped counter flow heat exchanger for decentral ventilation' is generally known as *Spiralflow*. The project started in February 2014 and ended in May 2016. ELFORSK has funded the project with 1.076.426 DKK while the partners have contributed with equity contribution of 1.141.754 DKK.

The project team is grateful for the finansial, commercial and personal support from Elforsk. A special thanks to Ditte, Jørn, Dorthe and Jesper.

During the project, several people have contributed to the development. A big acknowledgement to project participants: Christian Niepoort (Smith Innovation), Anders Lund Jansen (DTU/Sustain Solutions), Charlotte K. Larsen (Smith Innovation/Sustain Solutions), Henning Solfelt (PLH architects), Hasse Brønnum (Brønnum Plast), Torben Kirkholt (Ebmpapst). Svend Svendssen (DTU Civil engineering), Kevin Michael Smith, (DTU Civil engineering), Finn Agertoft (DTU Electro) and Cheol-ho Jeong (DTU Electro).

Partially based on his work with the development of Spiralflow Dr. Kevin Michael Smith from DTU Civil engineering wrote a ph.d. titled: "Development and Operation of Decentralized Ventilation for Indoor Climate and Energy Performance".

This end report is in English. A short resume is provided in Danish with the aim and results of the project. The Danish resume is in the beginning of the report. If further information is required, please contact Charlotte K. Larsen.

Resume (Danish)

Formål

Mekanisk ventilation er i stigende grad en nødvendighed for at sikre sunde boliger at bo i. Når facader tætnes, for at spare på varmen, kræves det at vinduerne åbnes mere end før tætningen, for at sikre et godt luftskifte. Dette er beboere i almindelighed ikke gode nok til og derved ophobes fugt og partikler i indeluften, og er med til at give fugtige boliger og dårligt helbred for beboere, bl.a. astma.

Mange boliger har ikke mekaniske ventilationsanlæg med varmegenvinding og det er ofte dyrt at etablere i eksisterende bygninger. Derfor er der et marked for rumbaserede decentrale ventilationsenheder med nem installation, der kan sikre behovsstyret mekanisk ventilation med høj varmegenvinding og lavt elforbrug, samt med mulighed for udluftning af overtemperaturer.

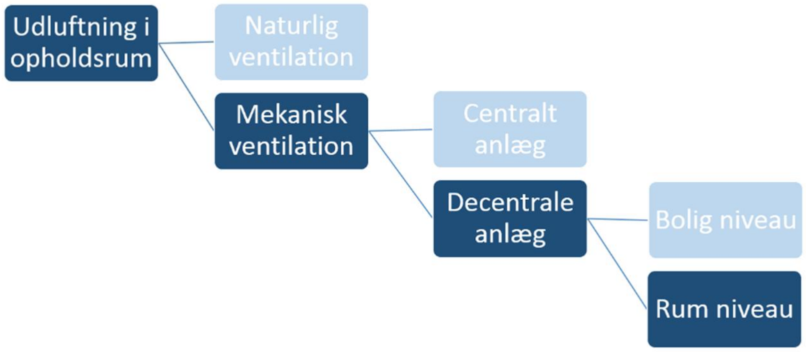

Figure 1- Overblik over ventilationstyper på markedet

Spiralflow handler om at lave en nyskabende varmeveksler til en decentral ventilationsenhed på rumniveau. Det er således selve kerneteknologien i en decentral ventilationsenhed projektet har adresseret.

Resultater

Produktet

Varmeveksleren vi har udviklet består af to 9 meter lange plastfolier, som rulles op med et mellemrum på 2 mm. Den korte afstand mellem lagene betyder, at der kan opnås en høj varmegenvindingsevne, hvis luften bliver jævnt fordelt mellem lagene og veksleren et tætnet korrekt. Plastfolien er 0,3 mm i tykkelsen.

Med konstruktionen af veksleren er der afprøvet forskellige løsninger. Den seneste udvikling er med ét luft indtag og ét afkast i hver ende.

En varmeveksler af plastfolie

Materialevalget for veksleren er yderst vigtigt – både for prisen men også for funktionaliteten. Fra projektets start har det været en plastfolie, der er blevet arbejdet med ud fra økonomiske betragtninger.

Det er vigtigt at materialet har gode termiske egenskaber, altså ikke deformerer under forskellige lufttemperaturer og samtidig er relativt stærkt, så det ikke giver efter for overtryk i luftlagene.

For at det var muligt at tætne veksleren i enderne var det ligeledes vigtigt at plastfolien havde en overflade med en god klæbeevne. Mange typer plast er inerte og kan derfor ikke svejses sammen eller limes. I projektet er der arbejdet med PVC-plast til prototyperne.

Høj varmegenvinding og lavt el forbrug

Der er i projektet lavet flere prototyper: Til start en lang enhed på 1,22m som fungerede som proof-of-concept, dernæst kortere vekslere på 28 og 34cm til placering inde i en væg. For proof-of-concept enheden er resultaterne meget lovende i form af en varmegenvinding på 75-85% for luftstrømme mellem 4,5 – 13,5 l/s. Med et meget lavt tryktab, som, hvis varmeveksleren blev installeret i et ventilationsanlæg, ville resultere i en samlet SEL-værdi på under 400 J/m^3. Kravene i BR15 er at SEL-værdien skal være under 1000 J/m^3, mens det forventes at blive strammet til 800 J/m^3 i 2020.

Testen af den 1,22m lange veksler har vist, at resultaterne er i tråd med de teoretisk simulerede og beregnede resultater, som var lavet før testene. Dog har det meget lave tryktab gjort at luftfordelingen og varmevekslingen bliver udfordret. For de kortere vekslere har luftfordelingen igennem veksleren været en udfordring. Det er derfor foreslået til videre fremfærd at indbygge strategisk placerede modstande, som vil give en god luftfordeling, og derved varmegenvinding, dog vil det give et forøget tryktab. Placeringen af disse modstande er derfor vigtig og skal udformes med omtanke.

God støj dæmpning

Der er lavet transmissionstøjsmålinger, som viser at installationen af varmeveksleren alene dæmper udvendig støj cirka ligeså meget som et standard vindue. Ved en endelig version af ventilationsenheden vil dæmpningen af støj kun blive bedre, da der vil være flere komponenter som afskærmer lyden udefra. Der vil derfor ikke være øgede støjgener fra udendørs (trafikstøj, gadestøj og lign.) ved at installere en decentral ventilationsenhed med den nye type veksler. Dette er et vigtigt resultat at tage med videre, da det potentielt kunne have sat en stopper for brugen af varmeveksleren.

Resume (English)

Aim of the Project

Mechanical ventilation is becoming more and more a necessity in residential homes in order to secure a healthy indoor environment. When facades are air tightened in order to save energy for heating a need for increased ventilation arisen, in order to secure a good air change which ensures a healthy environment. Residents are commonly known for not being good enough to open the windows. Humidity and particles are then accumulating in the indoor air. This provides humid living spaces and can lead to poor health conditions such as asthma, due to the growth of fungus.

Many residential homes does not have mechanical ventilation with heat recovery. Moreover, it is often expensive to install in existing buildings. There is therefore a market for room-based decentral ventilation units with easy installation. These units can ensure demand controlled mechanical ventilation with a high rate of heat recovery and a low power consumption. At the same time, they allow the possibility of venting when overheating occur.

The *Spiralflow* project is about creating a new heat exchanger for a room-based decentral ventilation unit. Thus it is the core technology in a decentral ventilation unit the project have addressed.

Results

The product

The heat exchanger we have developed consists of two 9m long plastic foils, which is rolled together with a 2mm gap in between. The short distance between the foils makes it possible to retrieve a high heat exchanging efficiency.

A variety of solutions for the heat exchanger has been tested. The latest development is a solution using only one air intake and one exhaust.

A plastic foil heat exchanger

The choice of material is highly important. Both regarding cost but also functionality. From the beginning of the project, a plastic foil has been chosen due to its low costs, flexibility and functionality.

It is important that the material have good stabile thermal capabilities, so it does not deform when subjected to different temperatures. At the same time the material has to be relatively strong so that it does not bend when over- or under pressure is present in the air channels.

In order to air tighten the heat exchanger it is also important for the plastic foil to have a surface with a good adhesiveness. Many types of plastics are inert and can therefore not be welted together nor glued.

A high rate of heat recovery and a low electrical consumption

Several prototypes have been tested in the project. As a proof-of-concept, a 1.22m long heat exchanger was constructed and followed by shorter heat exchangers of 28 and 34cm, fitted to be installed within a wall. The results of the proof-of-concept unit are highly promising. A heat exchanging efficiency between 75% og and 85% for air flows 4.5-13.5 l/s, with an extremely low pressure drop. Which, if installed in a ventilation unit would result in a SFP of less than 400 J/m^3. Current Danish requirements for SFP is that it has to be less than 1000 J/m^3, this is expected tightened to 800 J/m^3 by 2020.

The test of the 1.22m long unit has shown that the results are in line with the theoretical simulated and calculated results. The extremely low pressure drop has challenged the air distribution and heat recovery. For further development, it is suggested to work with strategic placed resistances, such as baffles or similar. The resistances will ensure a better air distribution and then an improved heat exchanging efficiency. It will however increase the pressure drop. The placement of these resistances are therefore important and shall be designed with care.

A good transmission noise sound dampening

There have been performed transmission noise measurements. The results shows that the installation of the heat exchanger itself reduces outdoor noise roughly as much as a standard window. When a final version of the ventilation unit is ready, the transmission noise sound dampening will be improved, since several components will shield the outdoor noise.

There is therefore no increased noise disturbance from the outside, e.g. traffic noise, street noise etc., when installing a decentral ventilation unit with the new type of heat exchanger. This is an important result as the noise reduction potentially could put an end to the use of the heat exchanger.

Basis for the Project

In order to meet the future requirements regarding energy consumption and indoor climate in both existing and new residences. There is a need for mechanical ventilation with a high rate of heat recovery and a low electricity consumption and with the possibility of venting for too high indoor temperatures. There is a very large, and rapidly growing, need for performing energy renovations of existing residential buildings in order to reach the goal, that all buildings in the year 2035 should be free of fossil fuels.

In older multi-storey buildings, it will be ideal to replace the old and poorly insulating and leaky windows with new highly insulated and airtight windows. At the same time there will be a need for installing mechanical ventilation with heat recovery in order to ensure a good air quality without draught and with a large energy saving. This mechanical ventilation can be a central ventilation system. However, it is often difficult and expensive to install in existing multi-storey residential buildings. Therefore there is a need for decentral ventilation units, which can be mounted in the exterior wall in each room and deliver balanced and demand controlled mechanical ventilation with high heat recovery and low electrical consumption.

The decentral ventilation units need to have great acoustic performance. Both regarding noise generated by the fans, but also from noise generated outside the building, e.g. traffic noise. In practice the occupant should not be able to hear that a decentral ventilation unit has been installed.

The Danish building regulation (BR) are now giving the opportunity for the use of demand-controlled ventilation. In BR 2015 (affective from 1st of January 2016) it is a demand for new buildings that the indoor temperature is allowed to exceed 27°C in maximum 100 hours per year. At the same time there are sharpened requirements regarding energy consumption. In order to avoid over heating it shall be possible to vent so the chill outdoor air can be used to cool down the building.

The airflows in the room-based decentral ventilation units can be regulated by changing the speed of the fans and thereby making it easy and inexpensive to exploit a demand-controlled ventilation strategy, where flow is adapted to the activity level in each room. Research has unveiled that there is a great need for boosting the ventilation level in bedrooms. At the same time, many Danish people prefer a cooler temperature in the bedrooms than the usual 20-22°C in the rest of the dwelling. These needs can be fulfilled by the use of a room-based decentral unit which ventilates the bedroom independent from the other rooms.

Interaction with other funded projects

The project team has in the former project “Decentral Komfort”, funded by Fornyelsesfonden and later Markedsmodningsfonden, worked with developing and maturing a whole decentral ventilation unit. The result are prototypes with a rotary heat exchanger, which are optimized in relation to design, function and interaction with existing installations. “Decentral Komfort” is market leading in regards to draft-free balanced airflows, efficiency factor, transmission noise and installation costs and is the foundation for the activities in “346-036 Novel spiral shaped counterflow heat-exchanger for decentral ventilation” (Spiralflow).

Spiralflow concerns the biggest challenge in the ventilation unit – the heat exchanger. The Spiralflow projects successor project, funded by ELFORSK, “348-046 Development and demonstration of an assembled prototype for decentral ventilation with a spiral shaped heat exchanger” seeks solutions for drainage of condensation water in inlet and outlet air, simple controls for low energy consumption, dehumidification of apartments and optimal indoor climate for residents.

The aim of the project

Vision

The overall vision is to realize energy savings and improve the indoor climate by creating an installation friendly industrial product which sets market standards in relation to indoor air quality, thermal comfort, low energy consumption, efficiency and low transmission noise.

The vision is to make the product as widely applicable as possible in relation to building typology and installation process so the international market potential can be exploited.

The challenge

The coming legislations regarding energy- and indoor climate for new housing combined with an urgent need to conduct energy-refurbishments in existing residential buildings creates big challenges in relation to securing a good indoor climate, having low total costs and a low energy consumption. The present solutions on the market are not capable to solve all these challenges in one effective solution.

In this project new ways of producing the heat exchanger have been examined with the goals of making it simple, energy-efficient, cheap and easy to mount. The end goal is to make a decentral ventilation unit with high heat recovery efficiency that requires no channels and at room-level can control the ventilation and temperature based on the actual demand.

The means to get there

In the project DTU Civil engineering, DTU Electro, Smith Innovation, Sustain Solutions, PLH architects, Brønnum Plast and Ebmpapst Denmark a new type of round heat exchanger for installation in exterior walls. The heat exchanger is constructed from a double spiral of plastic foil that forms a new configuration of the air channels and a new air distribution system. This makes it possible to control the two opposite airstreams and have the air streams distributed evenly over the heat exchanger. Special developed centrifugal fans are integrated in the air distribution system in both ends of the heat exchanger.
The spiral shaped counterflow heat exchanger will due to materials have a low production price and due to geometry have a relative large area for heat exchanging, which results in a high efficiency.

The aim of the project is to develop this type of heat exchanger up to a level where it can work as a core technology into the 'Decental Komfort" unit, se section 'Interaction with other funded projects'.

Market segmentation for decentral ventilation

There are numerous wall mounted decentral ventilation units on the market. These units are using different types of heat exchangers, which roughly can be divided into three main groups:

- Counter flow heat exchangers
- Regenerative heat exchangers
- Rotating heat exchangers (which is a type of regenerative heat exchanger)

There are advantages and disadvantages for each type of heat exchanger, see Table 1. The development of the spiral heat exchanger, which is a counter flow heat exchanger, should keep the advantages of counter flow heat exchangers while disadvantages such as pressure drop are improved. All of this, while production costs are kept at a minimum.

Comparison between different types of heat exchangers used in decentral ventilation	Parameter			
	Heat exchanging efficiency	Dehumidification	Cost	Electrical consumption
	[%]	[-]	[-]	[-]
Regenerative heat exchanger	60-80%	Poor	Low	Medium
Rotating heat exchanger	70-95%	Poor	Medium	Medium
Regular counter flow heat exchanger	80-90%	Good. But condensation	Medium	High, due to large pressure drop
Spiral shaped counter flow heat exchanger	80-90%	Good. Condensation, but with a drainage	Low	Low, due to low pressure drop

Table 1 – Comparison between different types of heat exchangers used in decentral ventilation units. Experience and numbers from http://sparenergi.dk/offentlig/installationer/ventilation/fakta, make the comparison.

Results

Heat exchanger models

Basic geometry

The spiral flow heat exchanger is made from two layers of foil, which are rolled up on the outside of an internal cylinder and fastened to the inside of an external cylinder. Inlet and exhaust air shall flow in opposite directions in the separated layers between the foils. The idea was simple, but when constructing the prototypes it turned out to be less simple to handle the foils, to secure even distances (2-3 mm) between the foils, to minimize tolerances and to seal the ends of the heat exchanger.

In the 'Decentral Komfort' project, we developed a unit with a rotary heat exchanger to be placed in an Ø260 mm hole in the façade wall. It is our goal to develop a Spiralflow unit with the same diameter and a similar length (250-300 mm).

Model A1

In order to construct the first model we calculated the length of the foils in total and per every half rotation. We went for a 2 mm distance between the foils, which our calculations estimated as the optimal when the length of the entire unit is 250 mm. We cut Ø3 holes in the centerline of both foils per every half rotation and we placed a stick through all the holes to stabilize the position of the foils. After some failures, we succeeded to roll-up the two foils and to place the stick through every layer.

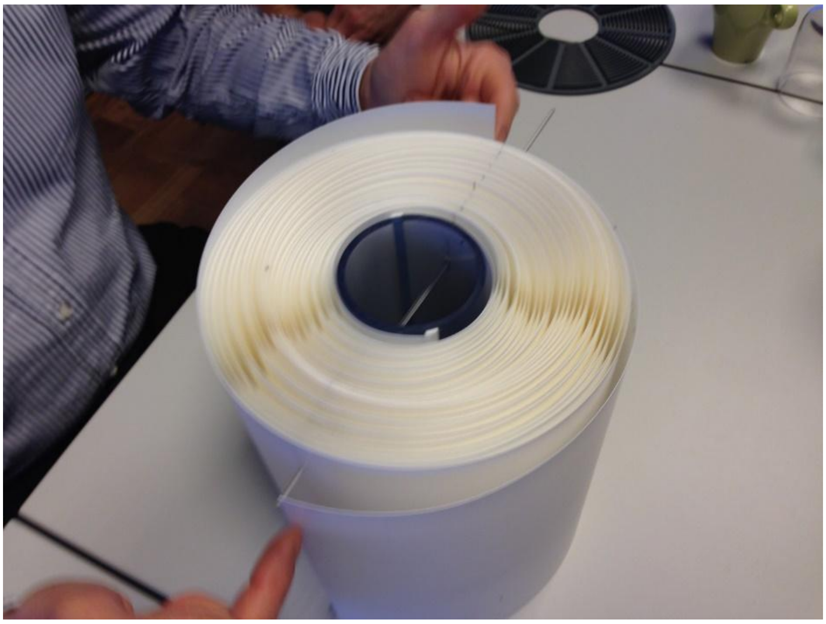

Figure 2 – picture of the roll up of model A1. The two plastic foils are rolled up into a double spiral using a 'stick' to hold the foils in position during the roll up.

At both ends of the heat exchanger, we have blocked sections of the gaps between the foils to separate the airflows in and out of the unit. By narrowing the sections of the blocked gaps, we expected to achieve smaller blind flow area between the foils and therefore a higher efficiency of the heat exchanger. We designed and produced two circular “grills” to cover the ends of the heat exchanger. There are 12 radial sections in each grill.

Figure 3 – Pictures of model A1 with the mounted 12 segments grill.

Within every second radial section, the grill blocks the inlet air gaps, and its neighbor sections blocks exhaust air gaps. The grill in the opposite end of the heat exchanger blocks opposite gaps.

Unfortunately, smoke tests showed large leakages around the grills that told us that the spiral geometry at the ends of the foil was not precise enough to fit with the grills. We also found leakages between the layers and the stick.

Driven by the above-described challenges, we went for two different development tracks, which we worked on in parallel. One track was to look for ways to roll-up the foils in a short heat exchanger with a 2 mm spacing distance between the foils and 280-340 mm long (Model A2 and A3. The other track was to develop a long heat exchanger with 3 mm distance between the foils and 1200 mm long (Model B). Assumingly it should be easier to roll the foils up with a 3 mm distance and to seal the gaps manually, but Model B needs to be placed inside the room because of its length.

Model A2 and A3

We investigated if the foils could be rolled-up with strips of spacer material between the foils. The most sufficient spacer material we could find is made of corrugated aluminum. The spacer was about 2.1 mm thick and was open for air flowing through it. We cut 20 mm wide strips and during the roll-up process we placed the spacer strips about 5 mm from the edges of the foils. We produced two models with different length to investigate how the length influenced on the efficiency of the heat exchanger. Model A2 is 280 mm long and Model A3 is 340 mm long. In continuation of the heat exchangers fans and pieces for separation of inlet and exhaust air were added and covered by internal and external hoods.

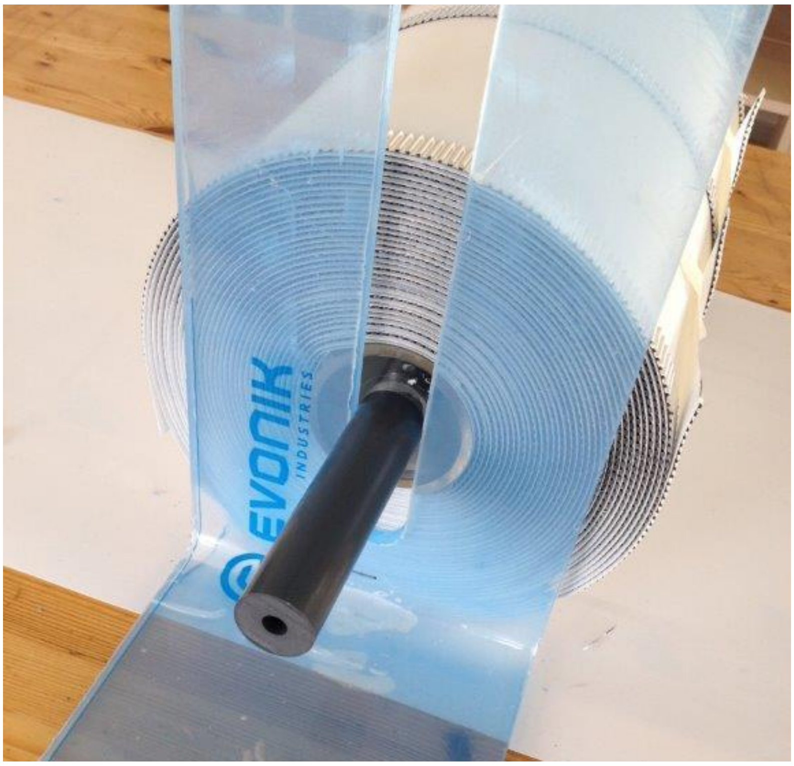

Figure 4 – Picture of roll up method used for model A2 and A3. A corrugated aluminum spacer has been used in the roll up, as seen on the picture.

We blocked the gaps between the foils differently in the models A2 and A3 than model in model A1. Instead of sectioning the ends in 12 radial parts, we simplified it to half circular sections. By hand we blocked every second opening with a sealant. The sealing resulted in a very tight blocking independent of the tolerances of the foil geometry. It worked, but it does not seem to be an industrial production process yet.

Model B

Our calculations showed that the length of the Spiralflow heat exchanger must be longer than the rotary heat exchanger to obtain the same efficiency. That is why we also wanted to build and test a very long heat exchanger. The length of the heat exchanger is 1.220 mm, equal to the standard width of the foil rolls. The space between the foils is 3 mm. Corrugated strips of plastic was used as spacer materiel and were rolled-up between each layer of foil. To handle the wide foils during the roll up process it was necessary to build a mounting tool. The sealing of the ends of the heat exchanger was made manually in half circular sections.

Figure 5 – Picture of preperation for the roll up of model B on the constructed roll up mounting tool. Each foil has plastic corrugated strips of 3mm in height mounted and is then rolled up on separate rolls. The foils will then be rolled together on a single roll creating a double spiral (the roll in the center of the picture).

When placing the heat exchanger inside a room it has to be insolated to avoid condensation of the indoor air. This meant that the diameter rose from Ø250 mm to approximately Ø320 mm. Also the length increased a lot, because space for fans and inlet/exhaust devices is added in continuation of the heat exchanger. A total length about 1.900 mm is expected for a final product. This can be installed above kitchen cupboards, in classrooms or other placements where an interior installation is accepted.

Predicted Performance

The dimensions of the heat exchangers were based on design constraints, such as length and the availability of materials, as well as calculations of expected efficiency and pressure drop to meet the project aims of 85% heat recovery and low fan power respectively.

Model A

The calculations of efficiency for model A1 assumed that supply and exhaust ran counter to each other, which is the orientation that would provide maximal efficiency. This was a reasonable assumption since the heat exchanger was divided into 12 sections, which should yield long and narrow airflows.

The calculations used the NTU-effectiveness method for counter-flow heat exchangers, see formulas. The predicted pressure drop was 12Pa at a flow rate of 15 L/s. The predicted efficiency at the same flow was 84.0 %. For a heat exchanger length of 235mm, allowing it to fit into a wall of two bricks, which is 250mm.

The heat exchanging efficiency was calculated by the following formula:

$$\varepsilon = \frac{NTU}{NTU + 1} \ [\%]$$

Where,

$$NTU = \frac{H \cdot A_C}{C_{inlet}} \ [-]$$

Where,

A_C [m^2] = The surface area including a reduction for dead zones

C_{inlet} [W/K] = The heat capacity of the inlet air

H [W/m^2K] = The total heat transfer coefficient

The calculations for model A2 also assumed counter-flow orientation but the effective area of the heat exchanger was reduced to account for dead zones adjacent to the seals at either end. This was an approximation, but it may not have been sufficient to account for the likelihood of perpendicular flows (i.e. cross-flow orientation) inside the heat exchanger. With the assumed A2 geometry as described in the previous section, the calculations predicted a heat exchanger efficiency of 83.2 % and a pressure drop of 15 Pa at 15 L/s. For a 280mm heat exchanger. The length of the heat exchanger was increased due to the change of concept from 12 to 2 sections.

The results for model A3, same model as A2 with increased length to 340mm, is 86.0% efficiency and a 18 Pa pressure drop.

Model B

The heat exchanger was expected to provide little resistance to air flow. The nominal flow rate of 15 L/s corresponded to a velocity of 0.88 m/s and likely resulted in laminar flow. Calculations predicted a total pressure loss of 34.0 Pa across the heat exchanger, which did not include filters. The NTU-effectiveness method predicted the efficiency using a heat transfer coefficient of 35 W/m^2K and a surface of approximately 13.5 m^2. Calculations used a reduced heat transfer surface due to expected dead zones adjacent to the seals at either end. It was assumed that this reduced area would account for the change in orientation of the two airflows, so the calculations assumed counter-current flow orientation. With balanced supply and exhaust, the calculations predicted 93% efficiency.

CFD Simulations of Model A2

As mentioned above, the calculations for model A2 and A3 assumed a counter-flow orientation of airflows, but this assumption was questionable. To investigate this further, a tool for computational fluid dynamics (CFD) was used to simulate airflows inside the outermost layer of the heat exchanger. In addition to the nominal dimensions, the simulations investigated the impact of longer and narrower dimensions for three basic flow rates (i.e. approx. 5, 10 and 15 L/s). This sought to find a better geometry to achieve a counter-flow orientation. Adding heat transfer dynamics was too computationally demanding, so the simulations only allowed a visual inspection of air flows, including velocities and pressures, using various plots.

The following table shows the effect of width and length on laminar flow in planar channels. The table shows the results for approximately 10 L/s through the heat exchanger, or an average entering velocity of 0.6 m/s. The red areas indicate dead zones and it appears that their relative area increases with decreasing length or width. These plots could help improve estimations of effective heat transfer area in future calculations. Additionally, the blue lines represent streamlines, so the lines for each flow would ideally run parallel to each other in a counter-flow heat exchanger. The images show that the narrower channels work as a counter-flow heat exchanger as expected. However, the streamlines of the wide layers appear to intersect more perpendicular to each other. This angle of incidence decreases with increasing length, which shows the benefit of a longer heat exchanger. This result could influence the maximum diameter and minimum length of the next generation of heat exchanger. This would ensure a small enough width and large enough length to maintain approximately counter-current orientations of flows and thereby improve efficiency to meet the targeted aims of efficiency.

Table 2. Mid-channel velocity magnitudes (0-1 m/s from red to green) and streamlines for different geometries of a single layer.

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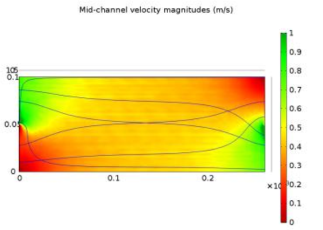
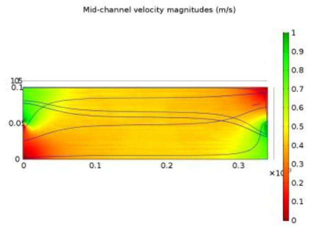
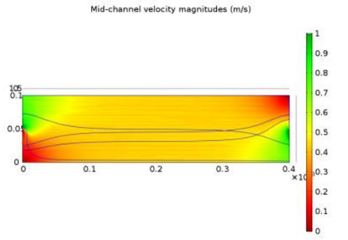
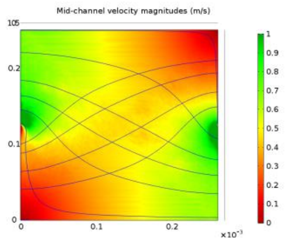
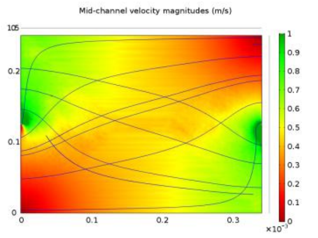
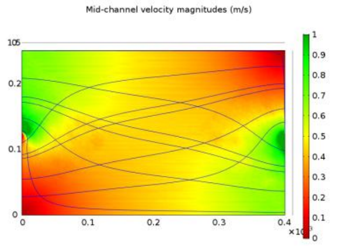
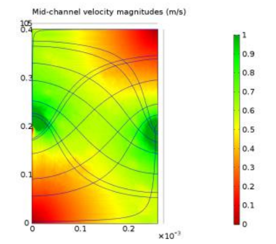
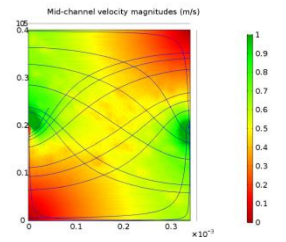
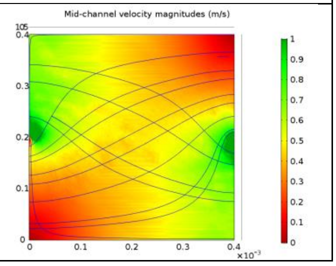
Width [m]	0.10			
	0.25			
	0.4			

Experimental Setup and Measurements

Leakage

All leakage tests were conducted with a vacuum cleaner, flow regulator, pressure differential sensor, and flow meter. Experiments measured both the internal and external leakage. For the internal leakage test, the vacuum cleaner was run at maximum power and the flow rate was measured through the heat exchanger. One end of the heat exchanger was then sealed, and the vacuum was regulated to create 20Pa pressure difference. The internal leakage was measured with the flow meter and the result was given as a percentage of the maximum flow.

To measure the external leakage, the heat exchanger was sealed and pressurised to 50 Pa with the vacuum cleaner. A flow meter was attached to the vacuum cleaner to measure the leakage. The external leakage was reported as a percentage of the maximum expected flow through the heat exchanger during regular operation.

Efficiency

Efficiency was measured by inserting the heat exchangers between warm and cold spaces and maintaining balanced airflows. The cold space was an insulated chamber that was maintained at a constant temperature between 0°C and 5°C. For model B, the warm side was simply a very large and open room at DTU. The large size of the room ensured constant warm side conditions. While conducting measurements for model B no condensation was observed to be dripping from the heat exchanger. This was important because the experiment targeted dry efficiency. To be certain that the test for model A2 was dry, the warm side of the heat exchanger was enclosed and maintained at a constant temperature while a de-humidifier ensured low relative humidity's. At least four temperature sensors were placed at the inlet and outlet of each airflow through the heat exchanger. The heat recovery efficiency was calculated as a ratio of the increase in temperature through the heat exchanger to the total temperature difference between the warm and cold spaces, which is a standard calculation for balanced airflows. The measured temperature efficiency was corrected for leakage. The pressure drop was measured by inserting probes perpendicular to air flows and measuring the drop in static pressure from the inlet to the outlet of the heat exchanger.

Experimental Results

Model A1

A preliminary inspection of the heat exchanger deemed it too leaky for further testing. Smoke was inserted at various locations while a fan pulled air through the supply or exhaust airside of the heat exchanger. The smoke visibly leaked between flows, and the air velocity did not appear to be evenly distributed across the heat exchanger surface. This is what motivated a change of design, as fewer sections for inlet and outlet would decrease the likelihood of improper seals between flows. It was also believed that fewer sections could improve the uniformity of the velocity profile at the inlet and outlet of the heat exchanger. The foreseen consequence was the possibility of perpendicular airflows in the heat exchanger instead of the desired parallel flows for counter-flow orientation.

Model A2

The internal leakage of the heat exchanger measured to be 3.2% at a flow of 6.3 L/s. This was a very strong first result and nearly placed the heat exchanger in the first class for internal leakage, which is less than 3%.

The efficiency was measured to be 73% at 8.9 L/s, and the interpolated result for 10 L/s was 71% based on the linear regression in the figure below. At 15 L/s the interpolated result was 64%. This was well below the expected result from calculations of predicted performance, which may indicate poor air distribution or flow orientation inside the heat exchanger. As indicated by the table below, the measured pressure drop was 28 Pa for a measured flow of 8.9 L/s, which is a positive result toward achieving low fan power with the designed heat exchanger.

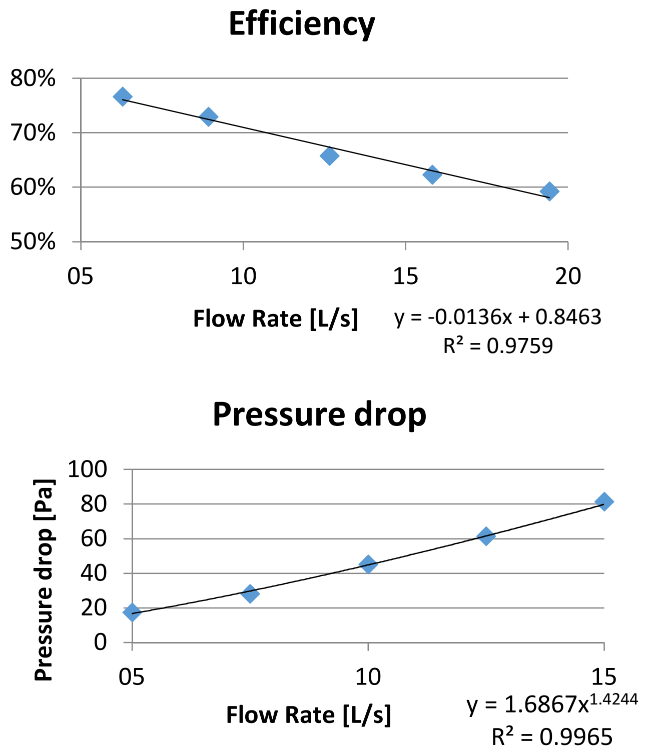


Figure 6 – On top a graph showing the heat exchanging efficiency, %, for various flow rates, l/s. Below a graph showing the pressure drop, Pa, for various flow rates, l/s.

Model B

Experiments measured the external leakage as 0.53 L/s at 50 Pa, which equates to 2.7% of maximum flow. The first class limit is 2% in the standard. A modified experiment measured the ratio of internal leakage (W) as 12.1% of ventilation flow. This did not satisfy the 10% limit and should be improved in future prototypes.

The temperature efficiency at the maximum corrected flow rate was 82.2% at 15 L/s. The measured pressure drop at this flow was 37 Pa, which compared well to the predicted value of 34 Pa. The NTU-effectiveness method predicted 93%, so the experiment provided a promising first result at this early stage of development. The efficiency remained stable for all flow rates, which may have implied a physical limit.

Transmission Noise

Airborne sound insulation measurements

Airborne sound insolation measurements were conducted in laboratory test facilities (called reverberation chambers of about 200 m^3) at the Technical University of Denmark with a partition wall of 10 m^2, where the unit under test was mounted. Two horizontally adjacent reverberation rooms are connected, one being the source room and the other being the receiving room.

Figure 1 illustrates a scheme of the measurements performed, where L1 refers to the averaged sound pressure level (SPL) in the source room, L2 to the SPL averaged in the receiver room, B2 refers to the background noise in the receiver room, and T2 refers to the reverberation time obtained in the receiver room. All levels and reverberation times are measured in 1/3 octave bands with the center frequencies from 100 Hz to 3150 Hz.

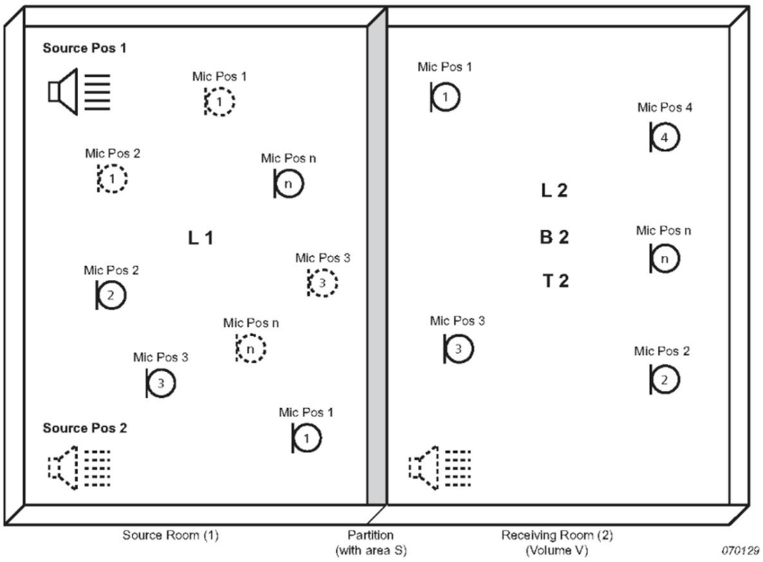


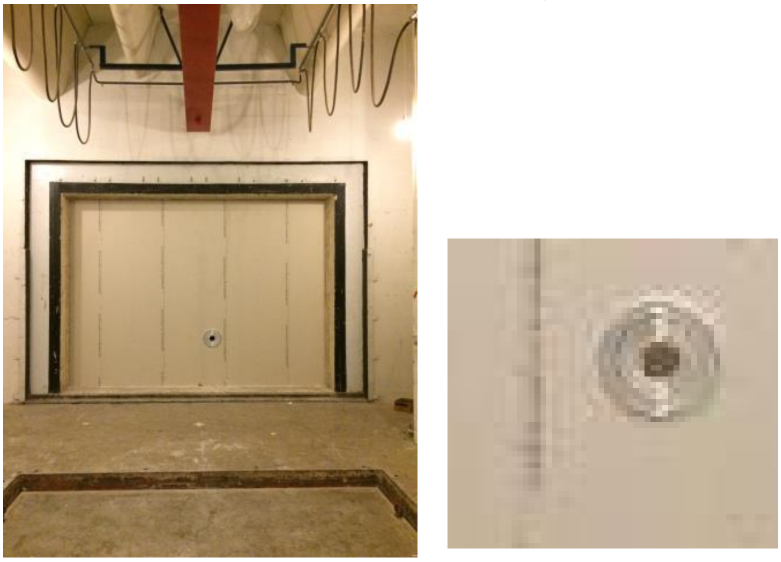
Figure 7 – Typical setup for sound insulation measurements.

The measurements were carried out following the standard ISO 10140-1:2010. Two fixed source positions were used with a level of around 95 dB. The average sound pressure levels were measured in the source and receiving room for 5 different positions with an averaging time of 10 seconds for each position. In the receiving room, the background noise was measured for 5 different positions and the reverberation time was measured with the interrupted noise method for 6 receiver positions. Based on these measurements, the element-normalized level difference of the unit under test, $D_{n,e}$, and the transmission loss, TL, of the wall were calculated. Figure 9 shows a picture of the different partitions measured.

$$D_{n,e} = L_1 - L_2 + 10 \log \left(\frac{A_0}{A} \right) [dB]$$

The weighted element-normalized level difference will be calculated by comparing the measured element-normalized level difference against a reference curves to obtain a single integer number rating. The value of the reference curve at 500 Hz is taken as the weighted element-normalized level difference.

(a) Wall (b) Long Unit



(c) Short Unit (d) Short Unit + Cardboard

Figure 8 – Pictures of the four different test setups during the tests.

Four different measurements were performed.

a. Measurements of just the wall. This is used as a reference measurement.
b. Long unit. With heat exchanger, fans and insulation.
c. Short unit. Only the heat exchanger of the short unit, without lids, fans, etc.
d. Short unit with cardboard. The same setup as setup c, but with cardboard on both sides of the centre tube in

the heat exchanger. The cardboard was added to resemble how the heat exchanger in the final shape will function.

For the long unit, the weighted element-normalized level difference is measured to be 45 dB with two different adaptation terms. The living activity adaptation C is -2 dB, and the urban noise traffic, C_{tr} is – 4 dB, indicating that the weighted element normalized level difference for a typical traffic noise spectrum is about 41 dB. For the short unit (heat exchanger itself), Dn,e,w becomes 30 dB, while with the cardboard blocking the hole of the heat changer has a slightly better performance of 33 dB.

	Dn,e,w	**C**	**C_tr**
Long unit	**45**	**-2**	**-4**
Short unit	**30**	**0**	**0**
Short unit + cardboard	**33**	**0**	**-1**

Table 3 – The weighted element-normalized level difference and adaptation terms.

SPL estimation in a typical bedroom

The sound pressure level is estimated for several installation scenarios (with and without the long/short unit) in a typical bed room (dimensions of 5 m x 3.7 m x 2.7 m). See figure 10 for the calculation configuration. There is a window of a 2 m^2, and the reverberation time is assumed to be 0.5 s. For a traffic noise of 60 dB, which is regarded as relatively loud, and we analyzed the following scenarios:

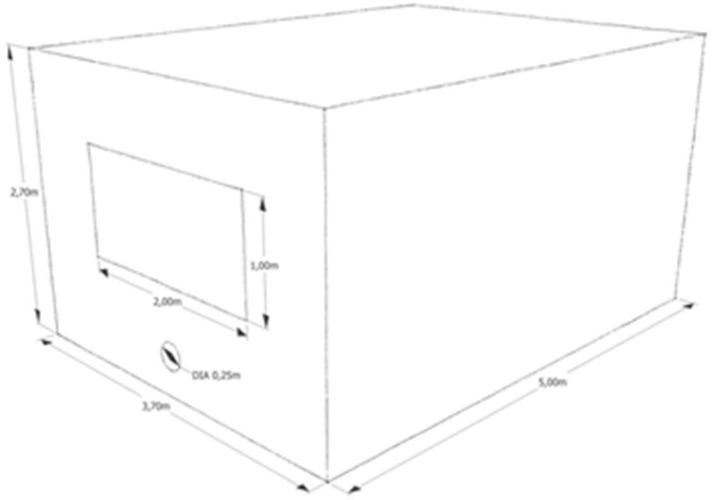


Figure 9 – A bedroom with a 2m^2 window and a ventilation unit.

Case	**SPL (dBA)**
Case 1 Wall + Window	34.4
Case 2 Wall + Window + Short Unit	39.6
Case 3 Wall + Window + Short Unit + CB	37.7
Case 4 Wall + Short Unit	38.1
Case 5 Wall + Short Unit + CB	35.1
Case 6 Wall + Long Unit	25.7

Table 4 – Sound Power Level, dBA, on interior side with a 60dB traffic noise on the exterior side

Discussion

Assembly

During the project we reached some promising results regarding the efficiency that worked as a first proof-of-concept. Challenges with the roll-up procedure and assembly made the results regarding manufacturability more open. The main assembly problems are:

The actual roll-up procedure of the plastic foil into a double spiral. The roll-up can be done in various ways with some simpler than others. The foil is 9 meter long and is difficult to handle into a precise roll-up with 2 mm between the layers. It was necessary to create unique "machinery" for the roll-up procedure.

The second main problem is the assembly of the plastic foil and attaching parts (e.g. the grill) to it. During the project period, we have worked with different kinds of assembly methods for the plastic foil and a grill that must be attached to the ends in order to distribute the air evenly between the layers. Mounting the grill proved difficult and smoke tests showed that the air streams were mixed in the ends of the heat exchanger. A simpler solution with a divider plate in the middle and a radial fan in each end was assumingly not as effective due to poorer air distribution.

Simplicity can make it easier (and therefore cheaper) to produce a heat exchanger, but it can also mean that the air distribution may be non-optimal which lowers heat recovery. The best trade-off between simplicity and heat recovery efficiency are still a "work in progress", meaning that tests are being conducted at DTU Civil Engineering with different lengths of the heat exchanger. Results of this will be used for developing a prototype of an entire decentral ventilation unit in the following project.

Efficiency, pressure drop and leakage

There is a constant trade-off between efficiency, production availability and leakage. In model A1 a good counter-current air flow orientation would have been ensured by the 12 sections. This would have resulted in a good heat exchanging efficiency. Unfortunately, model A1 was difficult to construct and it was not possible to make the design sufficiently air tight. This motivated the change of design to only 2 sections.

For model A2 the calculated level of efficiency was not obtained. A thorough CFD analysis revealed that the air distribution in model A2 was not optimal. For model B the calculated efficiencies were not obtained in experiments for the lower airflow rates. This was also due to air distribution, but for different reasons than for model A2. From the CFD analysis, model B should in fact have a good air distribution. The reason that the results for lower airflow rates did not follow the calculations was due to the configuration of fans and perhaps a too low pressure drop inside the heat exchanger. In order to fix this problem the heat exchanger could be placed in a unit with an improved assembly with respect to fan location and streamlined airflows. This would help to ensure more uniform pressures and air distributions.

Acoustics

The transmission noise test showed that the long unit insulates noise from the outdoors very well by reducing traffic noise of 60 dB on the exterior side to only 25.7 dBA on the interior side. This is significantly more than a standard window. The short unit does not have as good a noise reduction as the long unit. The short unit was tested without the final lids, fans, filters, etc. All these parts will help to obstruct the path of the sound and reduce noise. The short unit with cardboard best resembles how a final version of the heat exchanger will be. The short unit can reduce the 60dB traffic noise to 35.1 dBA on the interior side. This indicates that the final wall-mounted decentral ventilation unit with the short heat exchanger will be able to reduce the noise very well, as the short unit with cardboard almost reduces as much noise as a standard window. A final unit with lids, fans, bypass damper and filters will likely have better noise reduction than a standard window, and maybe at the same level as the long unit.

Conclusion

Throughout the project period the project team has been working loyally to the project's aim: To develop a new type of counter flow heat exchanger for a decentral ventilation unit. There have been lots of obstacles but several models have been constructed and tested at DTU to explore how a spiral shaped counter flow heat exchanger could be constructed.

The new type of counter flow heat exchanger will be able to fit into small wall-mounted and room-based decentral ventilation units. The new type of heat exchanger can be produced in different sizes with different dimensions fitted to different airflows. There is therefore not a limit to the room-based ventilation units. The heat exchanger can also be used in larger ventilation units, such as for classrooms, meeting rooms or similar locations.

The change of concept from 12 sections in model A1 to only 2 sections in models A2 and B resulted in far better leakage results but with a non-optimal heat exchanging efficiency. This was likely due to the airflow distribution inside the heat exchanger. This may be corrected with a longer and narrower heat exchanger or with an improved construction of the whole unit, including the location and position of fans. It may also be possible to introduce an airflow guide to ensure an appropriate air distribution.

The transmission noise results has ensured the project team that the use of the new type of heat exchanger in decentral ventilation units is possible. As noise in these types of units can be the most difficult parameter to comprehend.

Starting from scratch meant that it has not been possible to develop Spiralflow to mass-production just yet, but all decisions regarding its development has been taken with much respect to this issue. We will continue maturing Spiralflow in the following project where the scope is to assemble a whole decentral ventilation unit with this novel spiral shaped counter flow heat exchanger

Perspective

Future development and production of the heat exchanger

The project started as an idea to make a simple, feasible and cheap heat exchanger in terms of production. During the project a broad variety of assembly methods have been tested to show if they could seal the heat exchanger and therefore could be a feasible option for future production. With the overhanging condition that the assembly procedure must be able to be replicated when manufactured only one solution was acceptable.

In the future, it is of great importance that we clarify how to get the materials such as the spacer material in the right sizes. The spacer material keeps the right distance between the layers. The material we have used to the models developed in this project are from other technical products since it was hard to find a seller of single-faced corrugated metal or plastic strips.

The spiral heat exchanger is still too premature for production. An experimental project like this is only capable of making proof-of-concepts models, however the whole team have gained experiences with maturing the "Decentral Komfort"-project for production and is therefore knowledgeable about what is possible to manufacture.

The production of the Spiralflow heat exchanger must be matured during the next years. In the following project new partners are involved with professional skills within product maturation. The perspective is that they can optimize the existing models, so it can, by time, be produced at an assembly factory.

The spiral heat exchanger can be in the same shell as its predecessor "Decentral Komfort". This means that some of the parts are already produced, and the focus in the next project can be on functionality parts such as bypass, condensation drainage and the correct dimensions of the heat exchanger.

The following project 348-036

The project has a successor "Project 348-036 Development and demonstration of an assembled prototype for decentral ventilation with a spiral shaped heat exchanger", also funded by ELFORSK. The project starts 1st of July 2016 and lasts two years.

Our tests and calculations show that our spiral-shaped heat exchanger will be competitive regarding cost and heat recovery. Furthermore, when it is placed in a decentral ventilation unit it will outperform existing units regarding noise level, energy consumption and moisture control.

The following project aims to have all the results from the first project 346-036 come together in one decentral ventilation unit. This includes finding solutions for:

- Bypass
- Drainage of condensation
- Simple control, which ensures the lowest possible energy consumption
- proper dehumidification of buildings and an optimal indoor environment for residents
- Industrial production
- Design

One of the major results the project strives for is getting out of the lab and establishing a pilot test in real surroundings, which demonstrates how the spiral-shaped heat exchanger can help achieve the optimal interaction between energy consumption and indoor environment.