Final report

1. Project details

Project title	IEA IETS Annex XV XSQ: IEA Industrial Energy-related Technologies and Systems Annex XV Excess Heat Task 3
File no.	64020-2136
Name of the funding scheme	EUDP
Project managing company / institution	DTU Mekanik
CVR number (central business register)	30060946
Project partners	Weel & Sandvig and Viegand Maagøe
Submission date	31 December 2021

2. Summary

English version

The project has continued the Danish participation in Annex XV Industrial Excess Heat Recovery in the IEA industry program IETS. The annex is a longstanding annex – presently working on task 3 Combination of Methods and Operational Aspects for Industrial Excess Heat - Available Resources, Risk Minimization and Consequences of Future Changes in the Energy System. The task period was 1/11-2019 to 31/10-2021, while the present grant covers the work during 2021 only.

Annex XV Industrial Excess Heat Recovery deals with the efficient utilization of surplus heat in the industry, including the utilization of heat pumps to upgrade excess heat to useful energy. Denmark has significant ongoing activities related to heat pumps for industry and unique solutions for energy integration.

Task 3 is divided into:

Subtask 1 Combination of methods for excess heat identification and quantification

Subtask 2 Consequences for excess heat levels of future changes in industrial energy systems

Subtask 3 Operational aspects in industrial energy systems

Subtask 4 Opportunity and risk assessment for excess heat projects

Subtask 5 Compilation of innovative excess heat projects

The work focused on mapping relevant projects from the participating countries, collecting these under subtasks, and the learning that can be achieved. Almost 30 Danish projects have been registered, e.g., based on energiforskning.dk. The compiled projects have been discussed in meetings among the countries in the annex and a selection of them has been included in synthesis reports for each of the subtasks. Two Danish projects are included in subtask 1, one in subtask 2, and three in subtask 5. A complete Danish country report has been collected.

The project participants also participate in the National support group which supports the Danish Ex-Co representative. In connection with the support group, a workshop related to the work in annex XV task 3 was held with open participation for presenting the results.

Danish version

Projektet har fortsat den danske deltagelse i Annex XV Industrial Excess Heat Recovery i IEAs industriprogram IETS. Dette er et mangeårigt anneks – dette arbejde har drejet sig om Task 3 Kombination af metoder og operationelle aspekter for industriel overskudsvarme - Tilgængelige ressourcer, risikominimering og konsekvenser af fremtidige ændringer i energisystemet. Opgaveperioden var 1/11-2019 til 31/10-2021, mens den nuværende bevilling dækker arbejdet i løbet af 2021.

Annex XV Industriel overskudsvarmegenvinding omhandler effektiv udnyttelse af overskudsvarme i industrien, herunder udnyttelse af varmepumper til at opgradere overskudsvarme til nyttig energi. Danmark har betydelige løbende aktiviteter relateret til varmepumper i industrien og unikke løsninger for energiintegration.

Opgave 3 er opdelt i:

Delopgave 1 Kombination af metoder til identifikation og kvantificering af overskudsvarme

Delopgave 2 Konsekvenser for overskudsvarmeniveauer af fremtidige ændringer i industrielle energisystemer

Delopgave 3 Driftsaspekter i industrielle energisystemer

Delopgave 4 Muligheds- og risikovurdering for overskudsvarmeprojekter

Delopgave 5 Sammenstilling af innovative overskudsvarmeprojekter

Arbejdet fokuserede på at kortlægge relevante projekter fra de deltagende lande, samle disse under delopgaver og den læring, der kan opnås heraf. Der er registreret knap 30 danske projekter, blandt andet baseret på energiforskning.dk. De samlede projekter er blevet drøftet på møder mellem landene i annexet, og et udvalg af dem er indgået i synteserapporter for hver af delopgaverne. To danske projekter indgår i delopgave 1, et i delopgave 2 og tre i delopgave 5. Der er desuden samlet en dansk landerapport.

Projektdeltagerne medvirkede også i den Nationale støttegruppe, som støtter den danske Ex-Co-repræsentant. I forbindelse med støttegruppen blev der afholdt en workshop relateret til arbejdet i Annex XV Task 3 med åben deltagelse for præsentation af resultaterne.

3. Project objectives

Denmark has a tradition of developing energy-efficient technologies and equipment, and Danish industry has long been among the most energy-efficient worldwide. However, many other countries have also purposefully embarked on developing their industries towards higher energy efficiency and considerable research is being done into new technologies.

The work under the annex is closely related to Danish interests and objectives in the climate area. The industry's emissions of CO_2 account for more than 20% of Denmark's emissions (Energy Statistics 2018), which shows the importance of ensuring industry participation in the green transition.

This project deals with the utilization of the large energy resource that lies in industrial surplus heat. The project is broad and deals with a wide range of technical utilization opportunities and a review of framework conditions for the utilization of this resource in the various countries. Examples of applications include conversion to district heating, district cooling and electricity production.

This is also an area where most participating countries have a lot of experience, and where we from the Danish side, can benefit from the international experiences, e.g., in utilization of surplus heat for electricity production by organic Rankine cycles (ORC). Danish experience with the utilization of surplus heat from industry for district heating is of relevance for international promotion.

Excess heat has over time had a great focus, as it is a consequence of energy supply to a process and thus indicates a possible efficiency potential by optimizing the process and thereby reducing energy use. This has led to a focus on technology and methods for developing optimal solutions such as process integration and pinch analysis and the use of these and other types of mappings in the industry for the purpose of optimizing the processes. These methods and their application have also led to the further development of other, more applicable and / or more advanced methods with varying degrees of application in practice. The work with process integration methods in order to utilize surplus heat in industry is covered in the first tasks in annex XV.

Hence, annex XV task 3 is focused on the current initiatives in the area, and the latest developments around energy efficiency and reduction of surplus heat. This involves focusing on five topics that are considered to cover the latest contributions to state-of-the-art in the field:

Mapping, identification and quantification - In Denmark, this topic has been in focus in several projects with a focus on mapping and identifying potentials by utilizing available data.

Consequences of future measures for surplus heat, which is of great importance, as efficiency improvements, e.g., through process integration or heat pumping, result in less surplus heat and thus less opportunity for external supplies of heat.

Operational aspects for industrial energy systems focuses on variation in operation and thus the real potential of the plants.

Opportunities and risks related to economic, climate and energy potential as well as the barriers that lie in supply, investment needs, regulation, regulatory treatment, etc.

Catalogue of innovative projects related to surplus heat. A mapping has established a comprehensive collection of projects from the participating countries. These were analyzed in order to find agreement and differences between them. In this work, there has been a significant focus on heat pumps and electricity production with, for example, ORC, as well as energy storage.

4. Project implementation

The work has been based on the collection of recent projects within the scope of the task. For each of the a project template has been produced, including basic information about the project and specific information related to the task and the individual subtasks. The information has been collected in a matrix covering all projects and the specific subtask.

The interaction in the task has been conducted in form of online meetings between the participants hosted by the Austrian task management. Some of these have been deep dives for each subtask. In each meeting several of the participants have presented some of the project information, which has been collected for the task. Denmark has been involved in all meetings and has contributed by project presentations for bith the meetings and the deep dives.

The following meetings were held (only meetings in 2021 are funded by grant 64020-2136):

- Kickoff 3 October 2019
- Web conference 28 January 2020
- Web conference 2 April 2020
- Extended Web conference 25-26 June 2020
- Extended Web conference 18-19 January 2021
- Subtask Deep dives 22 to 29 April 2021
- Annex meeting 4 October 2021

The contributions from each participant have been discussed and evaluated, which has led to a selection of the most relevant projects to be included in the synthesis report of each subtask. In combination these form the basis for the main report of the task. This report is presently under preparation by the Austrian task management and will be completed during early 2022.

The Danish group has had one meeting 9 July 2021 and has participated in the combined Danish National Support Group and Annex status workshops 10 December 2020 and 17 November 2021.

5. Project results

The work has contributed to the task by mapping and supplying the requested information about relevant Danish projects related to industrial excess heat use. This information was initially gathered into a contribution matrix covering all projects from the participating countries: Austria, Canada, Denmark, France, Italy, Norway, Sweden, and Switzerland. At the project meetings, the proposed projects were discussed and then revised to fit into the final synthesis reports for each of the subtasks. The following projects were provided from the Danish partners to the task. Projects written in italic font are included in the final synthesis reports of the task. The contributions from Denmark are included in the appendix.

Subtask 1 Combination of methods for excess heat identification and quantification

- *Energy efficiency in the industry: A study of the methods, potentials and interactions with the energy system (own funding)*
- *Development of Process Integration Methodologies for Systematic Implementation in non-Energy Intensive Industries (own funding)*

Subtask 2 Consequences for excess heat levels of future changes in industrial energy systems

- *Development of ultra-high temperature hybrid heat pump for process application (EUDP)*
- Electrification of the Danish Food and Beverage Industry (Danish industry foundation)
- Electrification of processes and technologies for Danish Industry (Elforsk)
- Rational energy behavior in industrial companies (Elforsk)
- THERMCYC -- Advanced thermodynamic cycles utilising low-temperature heat sources (Innovation Fund Denmark)
- Waste Heat Utilization in Fish Industry (EUDP)
- Guide for heat recovery from industrial treatment plants based on two cases (Elforsk)
- Professional energy-flexible washing machines to smart grids (Elforsk)
- Direct contact heat exchanger with ice generation (DCHI) (Elforsk)
- Water vapor based heat pump systems (SteamHP) (Elforsk)
- Optimization of heat pump driven steam systems (Elforsk)
- Cooling plants using temperature glide systems (Elforsk)
- Highly efficient Thermodynamic Cycle with Isolated System Energy Charging (ISEC) (EUDP)
- SmartHeat (EU)
- Mixed refrigerant heat pumps/cooling systems (MIREHP) (EUDP)
- ELEC-TO-HEAT (EUDP)
- Compact thermochemical storage for residential heating systems using green electricity (Elforsk)
- Small-scale CSP — Numerical and experimental analysis of a novel thermal energy storage for a small-scale concentrated solar power plant (Horizon 2020)
- Sun-Charge — Solar thermal power with evaporation based storage for on-demand charging of electrical vehicles (EUDP)
- Two-phase expansion in turbo-expanders for organic Rankine cycle power systems (Eurotech)
- Waste heat recovery on Liquefied and natural gas-fueled (Danish Martime Fund, Orients Fund, Horizon 2020)
- Design of innovative low-cost expanders for organic Rankine cycle power (Eurotech)
- Experimental analysis of non-saturated two-phase heat transfer in plate heat exchangers for organic Rankine cycle applications (Own funding)
- PowerUp (EUDP)
- SuPrHeat – Sustainable process heating with high-temperature heat pumps using natural refrigerants (EUDP)

Subtask 3 Operational aspects in industrial energy systems

- ACT-ORC - Advanced Control of Organic Rankine Cycle Systems for Increased Efficiency of Heavy-Duty Transport (Horizon 2020)
- Smart management system for Industrial heat pumps (Elforsk)

Subtask 4 Opportunity and risk assessment for excess heat projects

- PowerUp (EUDP)

Subtask 5 Compilation of innovative excess heat projects

- *SuPrHeat – Sustainable process heating with high-temperature heat pumps using natural refrigerants (EUDP)*
- *Digital twins for large-scale heat pumps and refrigeration systems (EUDP)*
- *EnergyLab Nordhavn - New Urban Energy Infrastructure (EUDP)*
- *EnergyLab Nordhavn, Smart components in integrated energy systems (EUDP)*
- *EnergyLab Nordhavn |Platform for development of smart city energy solutions (EUDP)*
- *Experimental development of electric heat pumps in the Greater Copenhagen DH system - Phase 2 (EUDP)*
- THERMCYC -- Advanced thermodynamic cycles utilising low-temperature heat sources (Innovation Fund Denmark)

During the Task web conferences the following presentations were made:

- Riccardo Bergamini & Brian Elmegaard, *Identification of optimal measurement points for energy monitoring of industrial processes,* IEA IETS Annex XV Task 3, Subtask 1, January 18 2021
- Nasrin Arjomand Kermani, Brian Elmegaard, Selected Projects – Denmark-Subtask 2: ELIDI, Superheat and ChemStor, IEA IETS Annex XV Task 3, Subtask 2, January 18 2021
- Brian Elmegaard, *Digital twin for Waste water source heat pump for Copenhagen district heating*, IEA IETS Annex XV Task 3, Subtask 1, January 19 2021
- Fridolin Müller Holm, Utilization of waste heat In CP Kelco, IEA IETS Annex XV Task 3, Subtask 2, General systems, April 26 2021.
- Brian Elmegaard, *Danish contributions to IEA IETS Annex XV Task 3, Subtask 5*, IEA IETS Annex XV Task 3, Subtask 5, April 29 2021

For the Danish stakeholders two presentations have been made about the work in task. These have both been part of the IEA IETS National Support Group workshops. These were held on 10 December 2020 and 17 November 2021. At both Nasrin Arjomand Kermani presented the status of the work in Annex XV Task 3 – for the latter this included an extended presentation including the project results.

- Nasrin Arjomand Kermani, Task XV: Industrial Excess Heat Recovery - Technologies and Applications, National support meeting, IEA IETS Annex XV Task 3, December 10 2020.
- Nasrin Arjomand Kermani, Task XV: Industrial Excess Heat Recovery - Technologies and Applications, National support meeting, IEA IETS Annex XV Task 3, November 17 2021.

6. Utilisation of project results

The results of the in the form of the compiled synthesis provides a comprehensive collection of information about recent activities related to industrial excess heat in the participating countries. The focus of the work has been on the advanced and novel topics in the field as seen from the subtask topics. This has made it possible for the participants to present their contributions in view of these specific topics and potentially see their impact in a new way. For the Danish contributions, it has been valuable to complete a general screening of recent Danish R&D activities. These will be part of the final synthesis from the task and show that Denmark is still contributing to advancing the field. It is expected that the Danish contributions will be relevant for other countries, while some of the international contributions will be considered as inspiration for promoting new excess heat use solutions in Denmark. The work in the task has led to development of additional ideas for novel work – possibly as a new task in the annex – in which additional perspectives will be found. The Danish participants will participate actively in the development of a new annex task.

7. Project conclusion and perspective

- *State the conclusions made in the project.*
- *What are the next steps for the researched technology area?*
- *Put into perspective how the project results may influence future development.*
- *For ExCo delegates: list meeting attendance for meetings during the project period.*

The work under Annex XV Industrial Excess Heat Recovery Task 3 Combination of Methods and Operational Aspects for Industrial Excess Heat - Available Resources, Risk Minimization and Consequences of Future Changes in the Energy System has resulted in a comprehensive overview of recent work in the field of industrial excess heat and its minimization and optimal use. The task has extended the perspectives on this by coupling excess heat to combined methods for mapping, consequences of excess heat use, risk assessment, operational aspects, and innovative solutions for excess heat use. The Danish participants have provided an extensive list of 33 projects related to these topics, which shows recent advances in Denmark and their novel aspects. Six of the presented projects have been selected for extended presentation in the synthesis reports for the project.

The full compilation of results will be available for providing further ideas for new work on excess heat in a rapidly changing energy system with significant requirements for reaching the targets of the green transition, also in the field of industrial energy use.

8. Appendices

The list of Danish projects provided as contributions to the task are included as Appendix.

TB/RH/CD/AB

1. Annex 15 Phase 3 Project Contributions

Projects for Subtask 1

Project Name: Energy efficiency in the industry: A study of the methods, potentials and interactions with the energy system

Summary

In the presented project, the manufacturing industry was analysed to show its potential to improve energy use on an energy system and process level. For this purpose the inefficiencies of the industry sector of Denmark were taken as an example and quantified using energy and exergy methods. The developed models were used to quantify the amount of industrial excess heat. Based on these mappings, the potential for recovering and exploiting excess heat was analysed, which required the development of new methods to locate potentials. The methods included spatial, temporal and economic elements to have a realistic assessment of national potentials. This was complemented with multiple case studies, for which the model input uncertainties were taken into account. The second part of the project considered specific production processes and methods for assessing them. For the case study of a milk powder production system, different engineering and advanced thermodynamic methods were used for the analysis. The different methods, which include pinch and exergy analyses, located and quantified different optimisation potentials, which were compared against each other. At last, specific optimisation opportunities were identified and evaluated. These consisted of a retrofit heat exchanger network and the integration of heat pumps and solar thermal energy.

The results show that the energy efficiency of the Danish manufacturing industry was 80 % and only 72 % when taking the utility system into account. The losses are often in the form of recoverable excess heat. It was found that 1.5 TWh of excess heat could be cost-effectively used for district heating. The tool developed for the case studies enables to overcome some of the barriers for the utilisation of excess heat. It assesses heat sources and possible uses considering the uncertainties and determining important model parameters. The analysis of the dairy factory resulted in potentials for improvement and highlighted merits and drawbacks of the applied methods. The advanced methods allowed for a thorough analysis of components and interactions amongst each other, the engineering approach is quick to indicate possible improvement but requires experience. The specific improvement suggestions show that it is technically and economically possible to reduce energy use by means of heat integration and to partly replace the hot and cold utilities with more sustainable ones.

Further information on the project and the outcomes can be found in:
"Energy efficiency in the industry: A study of the methods, potentials and interactions with the energy system", PhD thesis, Fabian Bühler, 2018".

TB/RH/CD/AB

Introduction

The decline of fossil fuel resources and global environmental problems associated with their use make a transition to renewable energy sources necessary. A significant share of the energy consumption worldwide takes place in industry and it has been documented by numerous studies that a significant decrease of industrial demand may be obtained by taking energy system optimization and process integration into account in the early stages of any project, greenfield or retrofit. However, experience shows that there are several hurdles to pass, to make energy-optimal solutions state-of-art. These hurdles include acceptance, tradition, lack of knowledge about process energy requirements, lack of data, lack of interest, etc.

The Project aims at assessing and optimizing the industry as an integrated part of the energy system and support this by analysing and optimising specific production processes using advanced thermodynamic methods. The work was divided into two parts: (i) the sectoral analysis of industrial energy use and excess heat recovery and (ii) the analysis of industrial sites using different thermodynamic methods.

Aims and objectives

The project has two focus areas, namely the industry of a country or region and the industrial processes themselves. From these areas the main objectives consist in assessing and optimising the industry as an integrated part of the energy system and support this by analysing and optimising specific production processes using advanced thermodynamic methods.

In order to reach the targeted outcome, it is necessary to accomplish several objectives for the sector and process analysis respectively. On the sector level the following objectives can be defined:

- evaluate the energy resource conversion efficiency in the industrial sector
- determine the level of excess heat from industrial processes
- develop a method to analyse the utilisation potential of excess heat for district heating of a region or country
- determine possible barriers to the utilisation of excess heat in a national context
- develop a tool to locate and assess excess heat utilisation projects
- determine the uncertainties and important parameters in excess heat utilisation projects

TB/RH/CD/AB

To support the sectoral findings and case studies, industrial processes need to be analysed in detail using different methods, which have relevance for industry practice. For the given processes, the following objectives can be defined:

- develop models that describe the global behaviour of production systems including the utility supply
- identify the possible system interactions and improvements using multiple methods based on the pinch, energy and exergy concepts
- compare the applicability of these methods under different viewpoints to engineering approaches
- investigate the feasibility of replacing and improving current utility systems

Content and methodology

The project considered two main parts. First, an analysis of the manufacturing industry was performed, determining the efficiencies of the processes and utilities of different industry sectors. Based on this analysis the industrial excess heat and its utilisation potential with respect to the energy system was determined. The possible barriers to excess heat utilisation were shown and specific cases were analysed. For this analysis Denmark was used as a case study. Second, different methods for the analysis of industrial sites were applied to a case study to qualitatively compare the applicability and outcome of the methods. A focus of this analysis was on the comparison of engineering and advanced thermodynamic methods. The methods were applied to the case study of a milk powder production factory.

Industry and excess heat analysis

When analysing the industry it was found that the inclusion of the complete energy system and the accounting for the irreversibility of transformations, increased the significance and the interpretability of the results. In particular the comparison of different countries or industry sectors (e.g. dairy, cement or metal industries) is more meaningful, as a common basis with respect to the different energy carriers and their conversion is considered with these elements.
In a second step the amounts of excess heat were quantified. The process mapping used the energy end-use models created for the manufacturing industry, which allowed a detailed description of the excess heat with respect to temperature levels and processes. The THERM- CYC mapping relied on more aggregated assessments for processes on a sector level. This approach allowed the quantification of excess heat of all sectors in Denmark, but was limited with respect to the accuracy of the broad estimates. Though both methods are applicable to other countries, they were developed based on the available data for Denmark.
To find the possible utilisation potential of excess heat for district heating, an approach was developed which applied spatial, thermodynamic, temporal and economic elements to excess heat and district

heating data. This included the temperatures of the district heating supply and return for each network, the seasonal and daily profiles for heating demand and excess heat availability and the location of industrial sites and district heating networks. With this approach it was possible to establish a potential for excess heat utilisation which was refined through these elements. This allowed to find amongst others the requirement for heat pumps, thermal energy storage and unit costs of district heat. The required input to these models is also available or can be generated for other regions. Some parameters, such as the price of excess heat, have a great influence on the cost effectiveness. This price is only hardly assessable, as it depends on agreements and the local situation.

Barriers to the use of energy efficiency and excess heat utilisation were established by per- forming a literature review of national and international studies, analysing the tax and subsidy system and creating a case study. Altogether, this resulted in several barriers which were identified to be probably relevant for Denmark as local conditions were included. To confirm these findings the case studies have to be extended to include more companies and district heating representatives. The barriers found throughput the literature, were however consistent with respect to excess heat, thus a good indication for overcoming them could be given. The following are the most important identified barriers for excess heat utilisation. The lack of information about possible opportunities is a limiting factor. If information is available, the risks associated with the creation of dependencies between the industry and district heating supply were possible barriers on both sides. The district heating operator wants a long term investment, while the industry wants flexibility in changing their production. The taxes and subsidies were found to be not an actual barrier. This was also confirmed by the case studies for excess heat utilisation, were in most cases the taxes on electricity and the amount of subsidy were not the most important parameters. However, taxes were perceived as important by both industries and district heating companies.

One way to overcome the barriers was to create a tool which allowed to identify and evaluate cases for excess heat utilisation, without the requirement of finding additional data other then what was previously established. This tool can be used to pre-screen possible projects and evaluate their economic viability. It was found that the results of such a tool can have a great uncertainty, of which the users have to be aware. By implementing a tool for the sensitivity analysis, the users could efficiently reduce this uncertainty by improving a few key input.

The methods were to some extent built on data available for Denmark. The data used was to a large degree available from national and European public institutions, as well as utility companies and industry associations. Although the conclusions would be different, the applicability of the proposed methods to other regions and countries is discussed.

Industrial site analysis

One of the aims of the industry analysis, was to compare the suitability of different methods for the analysis of industrial systems, with respect to their energy use and efficiency improvement potential. The background was to give recommendations to industry professionals on the benefits of advanced methods. At first an engineering approach was applied, in which process data is benchmarked to other industrial sites or best practices. The outcome of this analysis depends thus heavily on the experience of the analyst. There were no clear guidelines available and the possible saving potentials were not directly quantified.

Pinch analysis, as an established method for the analysis of industrial systems, allows the determination of the heat integration potential, thereby giving a target for minimum energy use. It also gives hints for the design of heat exchanger networks and the placement of utilities. The more systematic approach to pinch analysis was found to be an advantage to the engineering approach.

For the exergy analysis, a model of the industry system was created, while the previous analyses only required the process stream data (flow rates, temperatures and loads). With the exergy analysis it was possible to determine the exergy efficiency, exergy destruction of each component and the losses of the system. This allows to locate the most inefficient components, to compare similar components and analyse the waste streams. However, the actual improvement potential remained unknown. To account for the real improvement potential and to study the system in more detail, an advanced exergy analysis was performed. While the results gave useful insights, in particular the share of unavoidable exergy destruction, the application of the method was limited. These limitations arose from the production system not being flexible enough to perform such an analysis, due to product set-points and, in a thermodynamic sense, unnecessary components. For the analyst, the advanced exergy analysis requires the most work. It is necessary to take many assumptions and gather more data besides multiple model evaluations are required.

The analysis of the industrial case studies is based on data which was obtained through data collection and measurements at the industrial sites or was provided from the industrial partners. The case studies are based on characteristics of one production unit, but he numerical models are generalized to some extent. Steady state or quasi steady-state conditions are assumed, and issues related to the dynamic behavior of the production processes are not taken into consideration.

Results

Denmark as a case study

The conversion efficiency of energy within the manufacturing industry was analysed for Denmark. In 2012, the industrial sector was found to have had an energy efficiency of 80 % and an exergy efficiency of 40 %. When including the conversion efficiencies of fuels to electricity and district heat at the utility sector, these efficiencies dropped to 70 % and 30 % respectively. This indicates, that high temperature processes with a high amounts of excess heat should be targeted, as large quantities of this heat are recoverable. The use of district heat and heat pumps for process heating, where the temperatures allow it, would further improve the site efficiencies.

With the THERMCYC mapping it was found that the transport sector had an estimated 76 PJ of recoverable excess heat, the utility sector 58 PJ and the industry sector 48 PJ. This mapping identified a low temperature excess heat potential below 60 ◦C of around 80 PJ, primarily from cooling and refrigeration processes, condensate and from industrial processes. The high temperature potential originated from combustion processes and exhaust gases and was found between 160 ◦C and 260 ◦C. The excess heat potential of thermal processes in the manufacturing industry, as found in the process mapping, was to a large extent located in this high temperature range. The main excess heat sources were in the oil refinery, building material (cement in particular) and chemical and food industry. In total 12.7 PJ of excess heat were found for the manufacturing industry using the process mapping.

TB/RH/CD/AB

The spatial analysis of the excess heat in Denmark showed that there are some industry locations with large amounts of excess heat. These large sources were found at the locations of oil refineries and the cement production plant. It was further established that approximately 1.36 TWh of district heat could be supplied from excess heat created in the manufacturing industry, which corresponds to 5.1 % of the district heating demand in Denmark. Heat pumps were required to make 36 % of the excess heat usable, considering the current supply temperatures of the district heating networks. Though excess heat from the considered processes will not be a major source for district heating on a national level, it can have great significance for several district heating networks.
When considering the socio-economic costs of using excess heat, it was found that these costs have a weighted mean of 35.6 €. MWh^{-1}. Large industrial sites were found to have generally lower costs for district heating, as the ratio of piping costs to the amount of heat delivered were low. In Denmark, a few large industries, dominated the results of usable excess heat potential.
The evaluation of several specific case studies and the creation of a tool for locating cases was developed for the use in Denmark. The analysed cases show that it is often cost efficient, from a private economic perspective, to deliver excess heat to district heating networks, other factories or to produce electricity. The final feasibility depends on a lot on the share of profits between the district heating company and the industry and the price of the obtainable in the local district heating area. The taxes for the use of excess heat were found to of relevance for the heating price when heat pumps with low COPs were used, but the temperatures and heat pump efficiency still remained the more important factors.

Milk powder production as a case study

Based on the performed analyses it was possible to identify several inefficiencies and saving potentials in the milk powder production factory. With the engineering approach the possibility of extending the regenerative heat transfer in several pasteurising units was shown, as well as a possibility for heat integration. The pinch analysis showed that the factory is already highly integrated and no apparent measures for heat integration existed. The inefficiencies in the hot utility supply were however shown and several free streams were identified, for which heat recovery measures could be applied. The exergy analysis also showed that the hot utility is inefficient. Approximately 62 % of the exergy destruction occur in the boiler and burner. In the heat treatment section more than 50 % of the exergy destruction took place in the three heaters. The advanced exergy analysis showed that less than 10 % of the exergy destruction in the heaters is avoidable, while this share is even less in the hot utility. Improvements in the production system, would however increase the exergy destruction in the current utility. This could be avoided by using for example a heat pump, as an increase in the return temperatures from the production would increase the heat pumps effectiveness.
Based on a simplified milk powder production case study, the creation of a heat exchanger network, the use of heat pumps and solar energy was analysed. The technical and economic analysis showed that the cooling demand could be reduced by 58 % and the heating demand by 33 %. This target was also achieved by designing a retrofit heat exchanger network, consisting of 4 regenerative heat exchangers. For each of the remaining cooling demand, the use of a heat pump to supply process cooling and heating was evaluated. With investments of payback times below 8 years, it would be

possible to almost cover all cooling requirements with heat pumps. The use of solar thermal energy was found to be profitable in two cases, namely for the heating of skim milk before entering the evaporator and the heating of drying air into the spray dryer. The payback times for these investments were 7 and 13 years, respectively.

Conclusion

The presented work be divided into two parts: (i) the sectoral analysis of industrial energy use and excess heat recovery and (ii) the analysis of industrial sites using different thermodynamic methods. The first part of the work deals with the sectoral analysis of industrial energy use, in which Denmark is taken as a case study, considering country-specific conditions (e.g. taxes, policies and existing energy infrastructure). The main findings and recommendations are therefore related to this case study.

The results show that the energy efficiency of the Danish manufacturing industry was 80 % and only 72 % when taking the utility system into account. The losses are often in the form of recoverable excess heat. It was found that 1.5 TWh of excess heat could be cost-effectively used for district heating. The spatial analysis of the excess heat in Denmark showed that there are some industry locations with large amounts of excess heat. These large sources were found at the locations of oil refineries and the cement production plant. It was further established that approximately 1.36 TWh of district heat could be supplied from excess heat created in the manufacturing industry, which corresponds to 5.1 % of the district heating demand in Denmark.

The evaluation of several specific case studies and the creation of a tool for locating cases was developed for the use in Denmark. The analysed cases show that it is often cost efficient, from a private economic perspective, to deliver excess heat to district heating networks, other factories or to produce electricity. The final feasibility depends on a lot on the share of profits between the district heating company and the industry and the price of the obtainable in the local district heating area. The taxes for the use of excess heat were found to of relevance for the heating price when heat pumps with low COPs were used, but the temperatures and heat pump efficiency still remained the more important factors.

The analysis of the dairy factory resulted in potentials for improvement and highlighted merits and drawbacks of the applied methods. The technical and economic analysis of the milk powder production case study showed that the cooling demand could be reduced by 58 % and the heating demand by 33 %. This target was also achieved by designing a retrofit heat exchanger network, consisting of 4 regenerative heat exchangers. For each of the remaining cooling demand, the use of a heat pump to supply process cooling and heating was evaluated. With investments of payback times below 8 years, it would be possible to almost cover all cooling requirements with heat pumps. The use of solar thermal energy was found to be profitable in two cases, namely for the heating of skim milk before entering the evaporator and the heating of drying air into the spray dryer. The payback times for these investments were 7 and 13 years, respectively.

TB/RH/CD/AB

Answers to the questions related to the subtask

1.1. Subtask 1

1.1.1. Questions

- How can we combine i.e. Pinch Analysis/HENS (with specific data requirements) with more qualitative input from questionnaires and/or insights from studies regarding individual industrial sectors (typical temperature levels/ heat loads for typical processes) to calculate excess heat potentials?
  - Process integration should be supported by any possible source of information in addition to actual measurements. This may include engineering judgement and estimates from onsite staff or experts or from relevant sources related to similar processes. In any case industrial production varies over time and measurements are uncertain, which mean that it is not exact results that will be available. Accordingly, the mapping will require modelling based on first principles to establish mass and energy balances. The use of GIS and databases for location and time variation of demand and excess heat makes it possible to clarify the true potential of integration between industrial sites and with surrounding district heating systems.
- How could these gaps be filled without collecting new measurement data?
  - This may include engineering judgement and estimates from onsite staff or experts or from relevant sources related to similar processes. The mapping will also require modelling based on first principles to establish mass and energy balances.
- What methods did you use in previous projects (e.g. pinch analysis, questionnaires, broader studies on a certain branch)?
  - Pinch analysis, process modelling based on first principles mapping, expert interviews, GIS, industry registration data bases
- Do you already use combined approaches?
  - Yes, as stated above.
- What auxiliary calculations did you perform in order to estimate excess heat potentials?
  - Process modelling based on first principles mapping and sensitivity analysis
- What obstacles did you encounter that would make a combination of information?
  - (Is something missing in the question formulation?)
  - The mapping and modelling requires significant efforts and time before it is possible to do the analysis.
- Is it possible to obtain sufficient data combining questionnaires and insights from previous studies? (e.g. combining information on equipment size, product throughput and information gathered from previous studies)
  - It is possible to complete a process integration study, but it is crucial to verify the accuracy, e.g., by sensitivity analysis.
- What requirements (data bases, data maintenance, knowledge on interconnections within the processes,…) need to be fulfilled in order to facilitate cross method approaches?

TB/RH/CD/AB

- The combination of onsite retrieval of information by discussion with staff of the facility and expert insights in processes in general may be important. GIS, industrial registration data bases.

Project Name: Development of Process Integration Methodologies for Systematic Implementation in non-Energy Intensive Industries

Summary

Process integration methods proved to be highly effective in analysing the energy utilisation of industrial facilities and identifying possible actions for increasing their energy efficiency. However, they are far from constituting the industrial practice. A major barrier to their use is the large time and resources required for performing the analysis. This issue is especially felt in non-energy-intensive industries, which are deemed to hide a large potential for energy savings. In fact, the low cost savings deriving from energy-efficiency projects in individual plants do not justify lengthy and expensive investigations. In this way, a large potential for energy saving which lays in non-obvious solutions is missed.

The project aimed at lowering this barrier by developing expeditious process integration retrofit methods. The most time-consuming activities of available methods were identified, and two novel methods were proposed, named “Required Data Reduction Analysis” (RDRA) and “Energy-Saving Decomposition” (ESD) method. They respectively aim at reducing the time consumption of the “data acquisition” and of the “design” phases of process integration retrofit projects. Their performance was tested and validated by applying them to nine case studies belonging to three different industrial sectors. This allowed to investigate their major merits and limitations and propose future development activities. The RDRA bases on the idea that measurements are performed to increase our knowledge, and this knowledge is quantifiable in terms of uncertainty. It employs uncertainty analysis, sensitivity analysis, and mathematical optimisation techniques in a systematic setting, to identify (i) a limited number of process parameters to measure, and (ii) the maximum acceptable uncertainty in their measurement. The ESD method builds on the idea that most of the energy-saving potential achievable by heat integration in existing industrial plants resides in a limited number of the process streams and of the “pinch violations”. It aims at reducing the solution space before embarking in the time-consuming design activities, avoiding to waste time in inspecting unfruitful solutions. This is achieved by two consecutive simplifications. The first identifies and eliminates useless process streams based on their energy-saving potential. The latter disregards heat exchangers responsible for cross-pinch heat transfer based on economic considerations

The results of RDRA’ s application to five case studies testify that it can significantly decrease the amount of parameters to measure, compared to what traditionally recommended. In all the cases, a maximum reduction of 86 % is achieved. The application of the ESD method to nine case studies proved

that it can significantly reduce the size of the problem and the time employed in formulating profitable design proposals with a reduction of considered process streams ranged from 33 % to 78 % compared to the total plant. All in all, the novel methods showed a high potential to lower the barriers to the use of process integration tools in the industry, potentially providing access to energy-saving opportunities today hidden.

Further information on the project and the outcomes can be found in:
“A study of the methods, potentials and interactions with the energy system process integration methods for retrofit of non-energy-intensive industries, PhD thesis, Riccardo Bergamini, 2020”.

Introduction

Process Integration (PI) methodologies have proved to be highly effective for identifying and assessing energy savings possibilities in the industry, both in existing processes and newly designed ones.

Despite their widely recognized performance and the complete generality of the concepts at their foundation, the aforementioned tools are mainly designed for utilization in large industrial processes and to such application they are, as today, relegated. This is mainly due to the high complexity level in their application, for both data collection and time required for the completion of the whole analysis. These barriers make the application of detailed process integration methodologies expensive, discouraging their usage in non-energy intensive industries, defined as industries with an average energy intensity lower than 250 Mtoe/M€ of value-added. Such processes embed lower individual energy savings opportunities, making it unfeasible to conduct a detailed analysis. However, due to their high number, they have a large aggregated energy consumption. Therefore, a large energy savings potential resides, unexploited, in the non-energy intensive industrial sector. A successful simplification of process integration methodologies would convince consultancy and process design companies in using such tools in the every-day practice. In addition, by using these methodologies, it would be possible to access the large energy savings potential unexploited in the non-energy intensive industrial sector.

Aims and objectives

This project aimed at developing expeditious process integration tools for process retrofit viable to be used especially in non-energy-intensive industrial sectors. The project built on one general hypothesis and three specific ones. The general hypothesis is that a large potential for energy savings resides, unexploited, in the non-energy intensive industrial sector. Based on this, three sub-hypothesis generate:

I. It is possible to reduce the time consumption of process integration studies without overlooking the largest energy-saving potential.
II. Expeditious process integration methods would convince consultancy and process design companies in using such tools in the every-day practice.
III. By using these methods it would be possible to access the large potential for energy savings unexploited in the non-energy-intensive industrial sector.

The work aimed at complementing the current state of research in the field by answering the following research questions:

- Which tasks of a process integration project require the largest amount of time and resources to be completed?
- What modifications to existing process integration methods could reduce the time required by these tasks?
- Are these modified methods generally applicable or is their use restricted to specific processes?
- How do the modified methods perform if compared to state-of-the art ones in terms of time requirement and level of insight provided to the analyst?
- Are expeditious process integration methods beneficial if compared to more rigorous ones in the retrofit of non-energy-intensive industrial processes?

Content and methodology

This work aimed at filling a renowned gap between academia and industry relative to energy analyses, in particular using process integration techniques: academic research often focuses on the development of more advanced and expensive analytical methods, while industry calls for easy-to-apply and expeditious tools (especially in non-energy-intensive sectors). This gap results in a suboptimal situation, in which the knowledge generated in academic research is not transferred to the industry, ultimately failing to benefit society towards a more sustainable production sector. The project focused on the development of expeditious, yet insightful, process integration retrofit tools. This was based on the hypothesis that a large potential for energy efficiency improvement is currently unexploited in the manufacturing sector and that such tools would allow to access it. As a result, two novel analytical methods have been proposed and tested on a total of nine case studies. The main developments and findings of the project, highlighting how they provided answer to the research questions. Only a few numerical results are given, showing the applicability and benefits of the proposed methods.

The two novel methods are briefly explained below:

<u>Required Data Reduction Analysis Method (RDRA)</u>

The RDRA method required data reduction analysis aims at reducing the time required in the data collection phase. It bases on the idea that measurements are conducted to increase our knowledge and that this knowledge is quantifiable in terms of uncertainty. The higher the uncertainty the lower the knowledge, and vice versa. As such, it employs uncertainty analysis, sensitivity analysis, and mathematical optimisation techniques in a systematic method composed of four steps, requiring only roughly acquired data as inputs. This allows to: (i) identify a reduced set of process parameters that should be measured with high accuracy and precision, and (ii) quantify the maximum acceptable uncertainty allowed in their acquisition, if a target maximum uncertainty should be achieved in the outputs of the energy analysis. This constitutes a systematic definition of “the right level of details” required in the data collection. Moreover, as all this is performed before investing a large amount of time in acquiring detailed data, it is expected to significantly reduce the time consumption of this phase.

TB/RH/CD/AB

Energy-Saving Decomposition Method (ESD)

The ESD method aims at reducing the time wasted in investigating unfruitful retrofit options in the Design phase. It bases on the idea that the 80/20 principle applies to energy-saving opportunities of existing plants, meaning that most of the energy-saving potential resides in a limited number of the process streams and is caused by a limited number of the so called "pinch violations". As such, the method systematically reduces the size of the solution space before embarking in the time-consuming design activities, avoiding wasting time in inspecting retrofit possibilities that would result in uninteresting investments. This is achieved by successively employing two simplification steps. The first is based on thermodynamics, using a novel factorial decomposition of the energy-saving potential of the plant. This allows to identify and disregard process streams that do not significantly contribute to the potential energy savings as a result of a better process integration. The second simplification step is based on economics, aiming at identifying process inefficiencies (in terms of "pinch violations") that, if reduced (or completely eliminated), would not result in economically attractive investments. This allows to focus the attention on reducing a limited number of large inefficiencies. This progressive reduction in the scope of the design problem is expected to both provide insight to the analyst, and to reduce the time wasted in inspecting unfruitful portions of the solution space.

Results

The following summarises the main developments and findings of the project, highlighting how they provided answer to the research questions.

Research question 1: which tasks of a process integration retrofit project require the largest amount of time and resources to be completed?

A review of the literature was performed aiming at identifying reported limitations of the currently available methods in the field of process integration, and the proposed attempts for solving them. Particular focus was placed on heat integration techniques for retrofit of existing industrial plants. The analysis revealed that several limitations were known in the field, out of which many still remain despite the forty years of development since the first tool for heat integration (i.e. pinch analysis) was proposed. They can be grouped in two categories based on the adversity they cause: (i) high time and resource consumption, and (ii) high risk of failure of the project. Both issues represent relevant barriers to the application of heat integration methods.

The tasks requiring the largest time and resources to be completed were identified to be Data collection, Process modelling, and Design, while the Targeting phase did not cause any time-related adversity. Out of them, the first is considered the most time consuming, while the remaining two are expected to require a similar time in a typical retrofit project (in which data availability is scarce and a process model is not readily available). More in detail:

(i) Data collection: A successful data collection requires acquiring data with "the right level of details". Too rough data would result in a misinterpretation of the problem, while too detailed data would result in a waste of time. As of today, no guidance is provided in identifying the right level of details by any available process integration method. As such, too detailed data is generally collected invoking the need of “being on the safe side”. This results in a significant time waste (possibly in the order of weeks).

(ii) Process modelling: The creation of a process model requires high process expertise and calls for the “right level of details” similarly to what discussed for Data collection, both for formulating and for validating the model. Also in this case, no guidance is provided by available methods risking to either misrepresent the problem (in case a too rough model is created) or employ resources in fruitless activities (in case a too detailed model is formulated).

(iii) Design: The design phase generally involves the detailed inspection and formulation of several design proposals, out of which most are found to be unacceptable investments when thermodynamic, economic, operability, complexity, safety, availability and maintenance considerations are accounted for. As such, their formulation proves to be a waste of time. A few methods have tried to limit the time waste by reducing the solution space identifying “portions” of the plant that are not expected to be involved in fruitful retrofit modifications. However, none of these methods have been accepted in the industrial practice due to different drawbacks, either causing a too long time to use the method itself, or negatively influencing the method effectiveness in removing truly unfruitful “portions” of the problem.

<u>Research question 2:</u> what modifications to existing process integration methods could reduce the time required by these tasks?
Based on the aforementioned review of the literature, the project focused on reducing the time wasted in the Data collection and in the Design phase of process integration retrofit projects. As a result, two novel methods were formulated: the Required Data Reduction Analysis (RDRA) and the Energy-Saving Decomposition (ESD) method. They complement existing process integration methods by providing expeditious and insightful information able to increase their time efficiency.

<u>Research question 3:</u> are these modified methods generally applicable or is their use restricted to specific processes?
The RDRA and the ESD method were tested on several case studies, whose data was either retrieved as part of the project, or from the literature. The former was applied to four milk powder production plants and a plant for the production of cheese. The latter was tested on these five plants, and four additional plants, two of which belonged to the pulp and paper sector and two to the petrochemical one. These nine case studies be-long to three different industrial sectors, and do not cover all the possible processes or sectors in the industry. Hence, there is no hard proof that the two novel methods would be unconditionally advantageous regardless of the process analysed. However, both the RDRA and the ESD method are general in their formulation and do not include any assumption related to the type of process to be investigated. As such, they are expected to be generally applicable.

<u>Research question 4:</u> how do the modified methods perform if compared to state-of-the art ones in terms of time requirement and level of insight provided to the analyst?

The application of the RDRA and the ESD method to nine different cases studies allowed to test their performance and verify the impact of assumptions required in their use. The following summarises the main outcomes for the specific methods.

RADRA Method: no tool available in the literature provides the same capabilities of the RDRA method. For this reason, it was not possible to benchmark its performance against existing methods. The following considerations solely ensued from the analysis performed in this project:

(i) The RDRA allowed to drastically reduce the number of parameters to consider in the detailed data collection phase of process integration retrofit projects. In all the five case studies analysed, the number of parameters requiring a detailed data collection was more than halved, achieving a maximum reduction equal to 86 % of the total parameters. It can be estimated that the time required in the successive data acquisition phase would experience a similar reduction.

(ii) The method was fast to apply, requiring a few hours to be completed in all the case studies, which were mostly employed for automatic computations. The interaction time required to the user was limited to maximum 30 minutes.

(iii) The optimisation routines proposed as part of the RDRA were effective in identifying: the maximum acceptable uncertainty in the input parameters when a predefined uncertainty in the output of the analysis was sought, and (ii) a set of process parameters of minimum size to be retrieved with the lowest possible uncertainty, given the measurement system available. These are not to be intended as global optima, but rather as local ones.

(iv) The insight provided while applying the RDRA allows to rationally and systematically identify "the right level of details" in the detailed data acquisition phase. This can provide additional benefits to the industry, apart from reducing the time requirement of process integration retrofit studies. In particular, it was proved that the RDRA can be used to aid the design of energy monitoring systems.

The ESD method: was applied to nine cased studies, comparing its performance to six different state-of-the-art methods for the retrofit of heat exchanger networks. The following can be concluded:

(i) The first simplification step of the ESD method allowed to significantly reduce the size of the problem in all the cases. This was quantified in terms of number of process streams removed from the analysis. The percentage reduction in number of streams ranged from 33 % to 78 %.

(ii) The second simplification step allowed a further reduction of the problem size. The number of heat exchangers causing inefficiencies ("pinch violations") to be considered for retrofit was significantly reduced in the five case studies this step was applied to. The reduction ranged from 66% to 88 %.

TB/RH/CD/AB

(iii) The two simplification routines are fast to apply and require a computational time in the order of minutes.
(iv) The reduction of the solution space achieved by applying the ESD method did not hinder the possibilities to identify profitable retrofit designs. The same retrofit design suggested with state-of-the-art methods was achieved in seven case studies, while even a better performing one was proposed in the remaining two.
(v) The success of the ESD method when compared to other state-of-the-art tools highlighted the importance of allowing engineering judgement in the design phase, warning against reposing absolute "faith" in optimisation routines. This was particularly evident in one case study, in which the ESD method allowed to formulate a retrofit that outperformed a well-established method employing automatic design procedures (the network pinch method), both in terms of achieved energy savings (9.1 MW versus 6.7 MW) and payback period (0.74 years versus 1.4 years).

<u>Research question 5</u>: are expeditious process integration methods beneficial if compared to more rigorous ones in the retrofit of non-energy-intensive industrial processes?
It can be generally expected that a trade-off between expedition and rigorousness in exploring the solution space exists: the lower the time dedicated in analysing possible solutions, the lower the rigorousness. As a matter of fact, the RDRA did not experience such a trade-off, as it allowed to both reduce the time required in the detailed data acquisition phase and to increase the insight achieved. On the other hand, the ESD method allows for it, by removing process streams and pinch violations from the problem, hence limiting the possible solutions of a retrofit project. As such, it was used for answering this research question. The trade-off was investigated by comparing the ESD method and the bridge framework while retrofitting the heat exchanger network of a milk powder production plant. The former method represents one of the most expeditious ones available to date, while the latter stems for one of the most rigorous.
The ESD method and the bridge framework identified the same final retrofit result. It achieved an energy cost reduction of 54 k€/y requiring an investment exhibiting an internal rate of return (IRR) comprised between 20 % and 50 %. However, the ESD method allowed to formulate just this one retrofit, while by means of the bridge framework a total of seven different designs were proposed. This constituted a significant reduction in time requirement without hindering the possibility to achieve the final retrofit design. On the other hand, it also resulted in a more limited investigation of the solution space. In fact, among the seven designs proposed with the bridge framework, two achieved an IRR higher than the proposed one. They were discarded as part of an open-ended decision-making activity based on risk and return considerations. This process was not explicitly conducted in the ESD method.
All in all it appears clear that a trade-off between expedition and rigorousness exists in the retrofit of heat exchanger networks. The analysis points out that it is recommendable to use expeditious tools such as the ESD method instead of rigorous and time-consuming ones in the retrofit of non-energy-intensive industries. This can be partly imputed to the nature of these processes: given the generally low monetary benefits derivable from energy-reduction investments, it is rarely justifiable to accept complex and risky solutions. This severely limits the number of acceptable solutions, increasing the risk of conducting unfruitful activities when employing too rigorous approaches.

TB/RH/CD/AB

Conclusion

The work consists in the formulation and validation of novel methods Required Data Reduction Analysis (RDRA) and Energy-Saving Decomposition (ESD) in the field of process integration. Both activities were performed using several industrial case studies as reference for applying the developed methods. They were either retrieved from previously published work or from novel investigations of currently operating production plants. For the latter category, up-to-date process data were retrieved and retrofit studies were conducted.

The results of RDRA' s application to five case studies testify that it can significantly decrease the amount of parameters to measure, compared to what traditionally recommended. In all the cases, the parameters to measure were more than halved, arriving at a maximum reduction of 86 %. Moreover, the method proved to be robust with respect to the assumptions required, and flexible in the scope of the analysis. It showed the potential to be employed combined to other energy analysis tools, and for designing industrial energy monitoring systems.

The application of the ESD method to nine case studies proved that it can significantly reduce the size of the problem and the time employed in formulating profitable design proposals. The reduction of considered process streams ranged from 33 % to 78 % compared to the total plant, and the reduction in "pinch violations" from 66 % to 88 %. Moreover, the comparison with six state-of-the-art process integration methods showed that this faster analysis allowed to identify the same or even a better solution of other tools, paying no price in terms of rigorousness.

All in all, the novel methods showed a high potential to lower the barriers to the use of process integration tools in the industry, potentially providing access to energy-saving opportunities today hidden.

Answers to the questions related to the subtask

1.1. Subtask 1

1.1.1 Questions

- How can we combine i.e. Pinch Analysis/HENS (with specific data requirements) with more qualitative input from questionnaires and/or insights from studies regarding individual industrial sectors (typical temperature levels/ heat loads for typical processes) to calculate excess heat potentials?
  - Process integration should be supported by any possible source of information in addition to actual measurements. This may include engineering judgement and estimates from onsite staff or experts or from relevant sources related to similar processes. In any case industrial production varies over time and measurements are uncertain, which mean that it is not exact results that will be available. Accordingly, the mapping will require modelling based on first principles to establish mass and

TB/RH/CD/AB

energy balances. It should also be supported by assessment of uncertainty and by substantial sensitivity analyses.

- How could these gaps be filled without collecting new measurement data?
  - This may include engineering judgement and estimates from onsite staff or experts or from relevant sources related to similar processes. The mapping will also require modelling based on first principles to establish mass and energy balances.

- What methods did you use in previous projects (e.g. pinch analysis, questionnaires, broader studies on a certain branch)?
  - Pinch analysis, process modelling based on first principles mapping, expert interviews, GIS, industry registration data bases
- Do you already use combined approaches?
  - The use of Required Data Reduction Analysis and Energy-Saving Decomposition makes it possible to identify the important measurements
- What auxiliary calculations did you perform in order to estimate excess heat potentials?
  - Process modelling based on first principles mapping and sensitivity analysis for applying the novel methods
- What obstacles did you encounter that would make a combination of information?
  - (Is something missing in the question formulation?)
  - Uncertainty analysis may require Monte Carlo methods – this leads to added complexity in the analysis.
- Is it possible to obtain sufficient data combining questionnaires and insights from previous studies? (e.g. combining information on equipment size, product throughput and information gathered from previous studies)
  - It is possible to complete a process integration study, but it is crucial to verify the accuracy, e.g., by sensitivity analysis.
- What requirements (data bases, data maintenance, knowledge on interconnections within the processes,…) need to be fulfilled in order to facilitate cross method approaches?
  - The combination of onsite retrieval of information by discussion with staff of the facility and expert insights in processes in general may be important. GIS, industrial registration data bases.

TB/RH/CD/AB

Projects for Subtask 2

Novel Heat Pumps

Project Name: Development of ultra-high temperature hybrid heat pump for process application

Summary

Industrial scale heat pumps have until recently been limited to maximum temperatures of 75 – 80 °C and thereby limiting the implementation of high temperature heat pumps. The hybrid heat pump combines the absorption and the compression process and uses water and ammonia as working pair. This makes it possible to reach temperatures above 80 °C using the standard industrial refrigeration components of today. This can be done with very high efficiencies and the process has proven to be reliable reaching the theoretical values of COP. The aim of the project was to increase the operating limits of the hybrid process by using the new standard components for higher pressures. Of the technologies for ultra-high temperature heat pumps, the hybrid process is without discussion the technology closest to the market.

The project consists of

- Theoretical and practical investigation of the hybrid heat pump process for ultra-high temperatures
- Investigation of possible implementation into the processes at the end users in the consortium and the conduction of a general market survey
- Demonstration at an end user in the consortium

To investigate the possibility of developing high temperature HACHP, numerical models were developed for the one-stage cycle and several identified two-stage compression configurations. The design of the hybrid absorption-compression heat pump (HACHP) governed by two extra degrees of freedom compared to the VCHP set by the choice of the rich ammonia mass fraction and the circulation ratio. The influence of these parameters on the performance and size of the system was investigated. The performance and size of the identified two-stage compression configurations were compared to the one-stage cycle. One two-stage compression cycle performs better than the remaining, in terms of increased efficiency, reduction of discharge temperature and needed compressor volume.

For the one-stage and the best two-stage cycle, the constraints of commercial components were imposed on the choice of rich ammonia mass fraction and the circulation ratio at a number of supply temperatures. This showed that the 28 bar one-stage HACHP allow temperatures up to 111 °C, 50 bar up to 129 °C, and 140 bar up to 147 °C. For the two stage HACHP, 28 bar components allow temperatures up to 126 °C, 50 bar up to 145 °C, and 140 bar up to 160 °C.

The working domain of the HACHP was investigated by imposing all technical constraints of commercial components to a variation of the heat supply temperature and temperature lift. An economic analysis was applied to the same variation such that the net present value in all points is attained. For all combinations, it was evaluated whether the solution complies with the technical and economic constraint (net present value > 0) and thus whether the heat pump implementation is feasible. A similar analysis was conducted for vapour compression heat pumps (VCHP), which allows a comparison, not only on which temperature levels and lift are attainable by the two technologies but also which technology is the more viable solution in the domain where both compete. This showed that the HACHP can be used to heat supply temperatures of 150 °C and temperature lifts up to 60 K. This increases the working domain of industrial heat pump. For the temperature range where the HACHP competes with ammonia VCHP: the HACHP is the most viable solution at low temperature lifts while VCHP are more profitable at high lifts. For the range where the HACHP competes with iso-butane or CO_2 the HACHP is always the more viable solution.

Further information on the outcomes of the project can be found in:
"Industrial heat pumps for high temperature process applications. A numerical study of theammonia-water hybrid absorption-compression heat pump, PhD thesis, Jensen, Jonas Kjær, 2016".

Introduction

Heat pumps can upgrade low temperature waste heat to a high temperature heat supply using only a fraction of primary energy, and therefore improve the energy efficiency of industrial processes.

Many industrial heat pumps have been installed with a heat supply temperature ranging from 50-90 °C. Commercial components for industrial heat pumps are limited to a working pressure of 28 bar, although high-pressure alternatives do exist for ammonia (50 bar) and CO_2 (140 bar). Most commercial compressors are not durable at compressor discharge temperature above 180 °C. Using these components, vapour compression heat pumps are limited to heat supply temperatures between 80 – 90 °C. Developing heat pumps that are capable of delivering temperatures above 90 °C may therefore allow heat pump implementation in more industrial processes than is currently possible.

The ammonia-water hybrid absorption-compression heat pump is of specific interest for development of high temperature heat pumps due to two properties inherent to the zeotropic working fluid: 1) Increased efficiency due to the reduction of thermal irreversibilities in the heat transfer processes between the working fluid and the external streams. 2) The reduction of vapour pressure compared to the vapour pressure of pure ammonia. The HACHP can therefore deliver higher temperatures at higher efficiencies than conventional VCHP.

Aims and objectives

The project aimed to contribute to the development of high temperature ammonia-water hybrid absorption-compression heat pump (HACHP) by investigating the following:

• Which HACHP cycle configurations are relevant and how are their performance influence by the choice of design parameters such as ammonia mass fraction and circulation ratio as well as operating conditions such as sink temperature glide, source temperature glide and temperature lift.

• What is the maximum heat supply temperature that can be attained by a HACHP within the range of commercial components currently available? Further, which of the component constraints limit the development of high temperature heat pumps?

• What are the main sources of irreversibilities as well as cost and environmental impact formation in a HACHP, to which extent are they interdependent and to which extent can they be avoided?

• How does the viability of a HACHP compare to the VCHP if a complete economic analysis is applied including both capital investment, maintenance and fuel cost over the lifetime of the system?

Content and methodology

A number of different methodologies were applied. In general, the methods applied have focused on numerical modelling and analysis. The work was initiated with the development of steady state thermodynamic models of different cycle configuration. Based on the thermodynamic models Second Law considerations were accounted for by the means of exergy and advanced exergy analysis. Numerical models where development for the design of heat transfer components which, combined with aggregated economic data allowed an overall evaluation of the viability of a hybrid heat pump installation.

A detailed list of the methods and investigations applied can be seen below:

• To investigate the performance of both one-stage and two-stage HACHP, thermodynamic models of the identified configurations are constructed. The identified configurations included internal heat exchange solutions, a bubble through inter-cooler solution and liquid injection solutions. Ammonia mass fraction and circulation ratio are identified as reasonable formulations of the extra degrees of freedom. Further, their influence of the performance is investigated through simulations of the constructed models. These simulations are conducted for a range of sink glide; source glide and temperature lift combinations.

• To evaluate the maximum heat supply temperature, the constraints of a range of commercially available components have been aggregated. These are imposed on a parameter variation of the ammonia mass fraction and circulation ratio to find the set of feasible combinations for each type of components at a range of heat supply temperature.

• In order to conduct a complete economic analysis and a life cycle assessment, component cost and material inventory most be identified. Cost and material mass functions have been constructed based on aggregated data from Danish intermittent trade business and individual producers.

• For the heat exchange equipment, estimating cost and material consumption requires the heat transfer area to be known. For this purpose the application of plate heat exchangers are assumed. Applicable heat transfer and pressure loss correlation are identified along with estimations methods for the ammonia-water mixture transport properties. The influence of plate dimensions as well as ammonia mass fraction are investigated to give design guidelines for plate absorbers and desorbers.

• To gain a deeper insight to the thermodynamic irreversibilities as well as the formation of cost and environmental impact an advanced exergy-based analysis is applied. An exergy based analysis consists of a exergy, exergoeconomic and exergo environmental analysis. In an advanced exergy-based analysis the interdependencies between component irreversibilities and dimensions is accounted for as well as the reduction potential. This increases the accuracy of the advanced analysis compared to the conventional exergy-based analysis.

• By combining the life time economic analysis of the HACHP with the identified technical constrains the working domain of the HACHP can be derived. The heat pump working domains is defined as the combinations of heat supply temperature and temperature lift at which heat pump implementation result in a technically feasible and economically viable solution. This analysis is conducted for both HACHP and VCHP. Having conducted the economic analysis gives the net present value (NPV) in the entire working domain. Thus, the most viable solution can be identified for heat supply temperature and temperature lift combinations were several technologies compete.

Results

Modelling and process optimization was applied to one one-stage HACHP and several two-stage HACHP. The performance of the identified system configurations were evaluated at several operating conditions. It was found that of the many suggestions given in literature to attain optimum COP none are valid at all operating conditions. Both sink and source glide matching as well as a constant concentration different can be applied at low sink source glides and low lifts. If both the sink glide and source glides are large, sink and source glide matching can be used to optimize COP for high ammonia mass fractions while only sink matching can be used at low ammonia mass fractions. For sink and source glides larger than 10 K it is recommended to optimize COP rather than match the glides of sink or source, as this will ensure a better performance of the HACHP.

All the identified two-stage configuration were compared with the one-stage HACHP in terms of coefficient of performance (COP), volumetric heat capacity (VHC) and compressor discharge temperature. This clearly showed that the two-stage configuration with internal heat exchange, is always the preferable two-stage configuration. This is regardless of the ammonia mass fraction and operating conditions.

The feasibility of high temperature HACHP development was investigated by imposing technical constraints and economic indicator constraints to a parameter variation of the ammonia mass fraction and circulation ratio. The set of feasible combinations was subsequently identified for three types of components: standard pressure (28 bar) components, high pressure ammonia (50 bar) components and transcritical CO_2 (140 bar) components. The results show that the HACHP is capable of delivering both higher heat supply temperatures and higher temperature lifts than conventional VCHP.

The maximum heat supply temperature was determined as the temperature at which no combination of ammonia mass fraction and circulation ratio result in a design that simultaneously satisfies all the imposed constraints. This showed that standard pressure components can be applied up to 111 °C in the one-stage HACHP and 126 °C in the two-stage. For the high pressure ammonia components the one-stage HACHP will allow a maximum temperature of 129 °C while the two-stage HACHP increases this to 146 °C. The transcritical CO_2 components can attain a heat supply up to 147 °C for the one-stage HACHP and 187 °C for the two-stage configuration. Removing the constraint on the vapour mass

TB/RH/CD/AB

fraction and increasing the compressor discharge temperature to 250 °C increases the allowable temperature for the two-stage HACHP to 215 °C for standard components, 225 °C for high pressure ammonia components and 231 °C for transcritical CO_2 components.

The dominating constraints when evaluating the maximum heat supply temperature are the high pressure, the compressor discharge temperature and the vapour ammonia mass fraction. If the attainable heat supply temperature of the HACHP is to be increased it is not sufficient to only increase allowable pressure, the allowable compressor discharge temperature and vapour ammonia mass fraction must also be increased. The sensitivity analysis shows that the highest influence on the high pressure stems from the absorber pinch point temperature difference, while the highest influence on the compressor discharge temperature stems from the isentropic efficiency of the compressor. On the other hand, vapour ammonia mass fraction is insensitive to the component inputs.

Further, it was found that reducing the sink/source temperature difference increases the maximum attainable heat supply temperature while reducing the maximum attainable lift. When comparing the Present value of the HACHP with the VCHP at the operating points where both are applicable: the cost of the HACHP is lower for almost all operating conditions with a heat supply temperature above 80 °C. For the range where the HACHP competes with R717 the difference in PV (present value) can be insignificant and both technologies should be considered. For the high temperature range where the only applicable VCHP technology is R600a the difference in PV is large and the HACHP should be applied.

Conventional and advanced exergy-based analysis was applied to the HACHP to identify the sources of thermodynamic irreversibilities as well as the sources of cost and environmental impact formation. The conventional exergy analysis showed that 72%of the total exergy destruction was located in the compressor (27%), absorber (24%) and desorber (21%). Thus, based on the conventional exergy analysis the first component to improve would be the compressor then the absorber followed by the desorber. Based on the conventional exergoeconomic analysis the most important component for system improvement is the compressor, as this has the highest total cost and the highest relative cost difference.

Based on the compressor's conventional exergoeconomic factor the total cost is dominated by investment. Applying the advanced exergy analysis showed that 27% of the total exergy destruction could not be avoided. Analysing the total avoidable exergy destruction associated to the component inefficiency, rearranged the order of importance. The three highest ranking components remain the same but the order is reversed: Desorber (38%), absorber (35%) and compressor (19%). In total 92%of the avoidable exergy destruction is allocated to these three components.

The advanced exergoeconomic analysis showed that 53%-54% of the system's avoidable total cost stems from the absorber. While the compressor total cost accounts for 20%-25% and the desorber 19%-20%. Also the exergoeconomic factors change when the advanced analysis is applied. The conventional analysis shows that the compressor, pump and desorber total cost are dominated by investment, while the absorber and IHEX total cost are dominated by the cost of exergy destruction. Applying the advanced analysis shows that only the IHEX total cost is dominated by investment while the compressor and absorber total cost are dominated by the cost of exergy destruction. The desorber is found to have a close to equal distribution of the investment and exergy destruction cost.

The environmental impact of the HACHP system was mainly driven by the operation of the system and thus linked to the electricity consumption. The environmental impact related to the construction of the system was found to be negligible and for all cases the environmental impact related to the increased size of the components could be justified by the decreased energy consumption over the life time of the system. Thus, the exergoenvironmental optimum was found at the unavoidable conditions. The unavoidable conditions were found not to be economically viable, wherefore a trade off was suggested, that reduced the environmental impact to a close to optimal solution, without any significant increase in cost. At this condition the advanced exergoenvironmental analysis was applied. This showed that 62% of the avoidable environmental impact was related to the compressor, followed by the absorber with 28%. 7% of the avoidable impact stems from the desorber while the last 3% were accounted to the internal HEX and pump.

Furthermore, the implementation of a HACHP in a spray drying facility was investigated and optimized. Heat transfer and pressure drop correlations from the open literature were gathered and implemented in the thermodynamic model of the HACHP. Cost functions based on Danish intermediate trade price were constructed to assess the heat pump investment. The exergoeconomic method has been used to minimize the total cost of the HACHP. The influence of ammonia mass fraction, circulation ratio and heat pump load was also investigated. Constraints based on commercially available technologies were imposed.
The best possible implementation was found to be a 895 kW HACHP with an ammonia mass fraction of 0.82 and circulation ratio of 0.43. This resulted in an economic saving with a present value of €146.426 and a yearly reduction of the CO_2 emissions by 227 ton.

Conclusion

A procedure for thermodynamic modelling of HACHP was presented and several two-stage compression configurations were identified. All identified configurations were modelled such that the performance of the cycle could be compared. All in all if the sink and source glides are larger than 10 K. it is recommended to optimize COP rather than match the glides of the sink or source, as this will ensure a better performance of the HACHP. All the identified two-stage configuration were compared with the one-stage HACHP in terms of COP, VHC and compressor discharge temperature. This clearly showed that the two-stage configuration with internal heat exchange, always is the preferable.

The feasible working domain of a HACHP has been evaluated based on a detailed economic analysis and a comprehensive investigation of the design variables: ammonia mass fraction and circulation ratio. The results show that the HACHP is capable of delivering both higher heat supply temperatures and higher temperature lifts (up to 150 °C and 60 K with commercially available components respectively) than conventional VCHP.

A conventional and advanced exergy-based analysis is applied to the HACHP. The results from the conventional exergy analysis showed that 72 % of the total exergy destruction was located in the compressor (27 %), absorber (24 %) and desorber (21 %). Applying the advanced exergy analysis showed that 27 % of the total exergy destruction could not be avoided. . The three highest ranking components remain the same but the order is reversed: Desorber (38 %), absorber (35 %) and compressor (19 %). In total 92 % of the avoidable exergy destruction can be allocated to these three components. The advanced exergoeconomic analysis shows that 53 % - 54 % of the avoidable total cost stems from the absorber. While the compressor total cost accounts for 20 % - 25 % and the desorber 19 % - 20 %. This differs significantly from the results of the conventional analysis.

Answers to the questions related to the subtask

1.2. Subtask 2

1.2.1. Questions

Novel Heat Pumps:

- What is the aimed technology/system improvement?
  - The HACHP may reach higher temperature levels at reasonable pressure, and hence it can be competitive for industry – in particular for application with temperature glide due to the zeotropic nature of the mixture.
- Temperature levels?
  - The target temperatures are up to 150 °C.
- Novel high efficiency components? Other?

  The heat exchanger for evaporation and condensation of zeotropic mixtures, i.e., desorber and absorber, respectively, and the vapour-liquid separation of the working fluid.

Here is the list and brief descriptions of other relevant projects from Denmark in Subtask 2 provided to IETS (for further information on projects, please contact the Danish Authors):

Electrification of the Danish Food and Beverage Industry (Financed by the Danish industry foundation; Project leader and partners: VIEGAND & MAAGØE ApS (Leader), DTU Mekanik, Landbrug og Fødevarer, Dansk Industry, Dansk Energi; Project period:2020-2022), **Subtask 2, General Systems**

The project electrification of the food and beverage industry will use 20 concrete cases in selected Danish food companies to illustrate how industrial processes can be converted from fossil fuels to electricity. A primary goal of the project is to propagate the experiences learned from the 20 cases to the entire Danish food and beverage industry.

Electrification of processes and technologies for Danish Industry (Financed by Elforsk; Project leader and partners: DTU Mekanik (Leader), Teknologisk Institut, VIEGAND & MAAGØE ApS , SAN Electro Heat, Labotek, CP Kelco , De Forenede Dampvaskerier A/S; Project period: 2018-2020), **Subtask 2, General Systems**

The potential for realization of an optimal approach for substitution of fossil fuels by 100% electricity is identified, during the project. For processes in specific industries, solutions will be developed for efficient integrations as well as specifications for developments and test existing equipment.

Rational energy behavior in industrial companies (Financed by Elforsk; Project leader and partners: Dansk Energi Management A/S(Leader), FlexMeter; Project period: 2019-2020), **Subtask 2, General system**

The project will expand on a proved concept for energy conservation in large kitchens, combining precise measuring with tailormade advice on behavior change, and develop this concept into a more generic concept that can be offered to a wide range of industrial companies.

THERMCYC -- Advanced thermodynamic cycles utilising low-temperature heat sources (Financed by InnovationsfondenTidl. Strategiske Forskningsråd; Project leader and partners: DTU Mechanic Engineering Department (Leader) and Chemical Engineering Department, Technical University of Denmark, VIEGAND & MAAGØE ApS, A.P. MØLLER - MÆRSK A/S, Danfoss A/S, ARLA FOODS AMBA, Alfa Laval Sweden, Viking Heat Engines AS, Technische Universität München, Aalborg Universitet, Alfa Laval Aalbog A/S, MAN Diesel & Turbo, Delft University of Technology; Project period: 2014 - 2019), **Subtask 2, General Systems**

The project aims at solutions for thermal plants, for power generation, heat pumping and cooling by use of low value sources as waste heat and renewable sources at high efficiency. During the project, the design of both processes and working fluids to achieve significant energy savings has been developed.

Waste Heat Utilization in Fish Industry (Financed by EUDP; Project leader and partners: TrippleNine (Leader), SiccaDania; Project period: 2016-2019)**, Subtask 2, General Systems**

The purpose of this project is to design and test equipment that makes it possible to use low temperature waste heat for the cooking of industry fish instead of fuel based heat from a boiler. The main equipment is a heat exchanger capable of handling whole or roughly shredded fish without clogging.

Guide for heat recovery from industrial treatment plants based on two cases (Financed by Elforsk; Project leader and partners: Professionhøjskolen VIA univeristy college (Leader), Aqua Service A/S, VERDO A/S, DHI, BHJ A/S, DANPO; Project period: 2016-2018)**, Subtask 2, General Systems**

The project will through the analysis of two industrial treatment plants identify the potential for energy savings by utilizing excess heat and ensure proper temperature in the purification process using heat pumps. The project will summarize the results in a guide for heat recovery from industrial water treatment plants.

Professional energy-flexible washing machines to smart grids (Financed by Elforsk; Project leader and partners: Teknologisk Institut (Leader), MIELE A/S, ELECTROLUX PROFESSIONAL A/S, Saniva Facility A/S, Asko/Gorenje, SERVICE CENTRALEN A/S, Group Nordic , Kolding commune; Project period: 2012-2017), **Subtask 2, General system**

Washing and eventually dishwashers and dryers which use hot water or heating with heat exchanger, tested for energy efficiency, washing and wash quality and these laundries potential to exploit heat storage mapped. These machines can utilize environmentally friendly energy sources such as district heating, heat pumps and solar heating.

Direct contact heat exchanger with ice generation (DCHI) (Financed by ELFORSK; Project leader and partners: Teknologisk Institut (Leader), JOHNSON CONTROLS DENMARK ApS, ARLA FOODS AMBA, Augustenborg Fjernvarme a.m.b.a., SPX FLOW TECHNOLOGY DANMARK A/S; Project period: 2014 - 2018)**, Subtask 2, General system**

Development of a compact, efficient and cheap direct contact heat exchangers with ice generation, to absorb heat in water vapor based refrigeration and heat pump systems, enables increased COP at temperatures around the freezing point (e.g. ice-water systems, ice generators, heat pumps). Traditional refrigeration and heat pump systems do not allow ice formation and are thus not used below the freezing point.

Water vapor based heat pump systems (SteamHP) (Financed by Elforsk; Project leader and partners: Teknologisk institute (Leader), ROTREX A/S, JOHNSON CONTROLS DENMARK ApS, Krammer Innovation, Pentair; Project period: 2018-2021), **Subtask 2, Novel Heat pump**

There is a need for high temperature heat pumps in converting process heating to the el-based energy system of the future. Water vapor is an efficient and accepted working media for heat pumps above 100°C. The project will bring the development of solutions based on the Rotrex compressor to the market.

Optimization of heat pump driven steam systems (Financed by Elforsk; Project leader and partners: Teknologisk institute (Leader), E-Tek ApS, Stryhns A/S, Ardo A/S (Frigodan), AURA Rådgivning A/S, C&D Foods, BERENDSEN TEXTIL SERVICE A/S, Innoterm A/S, Solid Energy A/S; Project period: 2019-2021), **Subtask 2 , Novel Heat pump**

In the project, a concept for the establishment and optimization of heat pump based steam production systems is developed based on the use of latest technology in components and regulation based on a demand-driven approach. The demand driven approach to system optimization and its methods including necessary registrations is used in an optimization tool for energy optimization and design of new steam systems, and retrofit of existing systems. In addition, the methods are documented in a guide based on a methodological approach illustrated with examples based on the situations of the participating companies, so that the possibilities are indicated and illustrated in concrete cases. .

Cooling plants using temperature glide systems (Financed by Elforsk; Project leader and partners: JoMa Tech MSR IvS (Leader), Teknologisk institute, DTU Mekanik; Project period: 2017-2019), **Subtask 2, Novel Heat Pumps**

The project proposes a heat pump cycle configuration combining compression and condensation in one single unit and evaporation and expansion in another separate unit while benefiting from the advantages of liquid refrigerant injection into both units at proper time to achieve temperature glide that matches the heat sink, e.g., a district heating system. The performance of the proposed cycle was examined by numerical modeling of the cycle and development of a test rig for further verification of the results.

Highly efficient Thermodynamic Cycle with Isolated System Energy Charging (ISEC) (Financed by EUDP; Project leader and partners: Teknologisk Institut (Leader), innotek, METRO THERM A/S, Svedan, ARLA FOODS AMBA, ALFA LAVAL COPENHAGEN A/S, Bjerringbro Fjernvarme, Technical University of Denmark; Project period: 2013-2016), **Subtask 2, Novel Heat Pumps**

The objective is to demonstrate an improvement in the energy efficiency of heat pumps with up to 50 % by using a novel technology where heat pumps are operated together with an optimal usage of storages, which will reduce the average temperature level in the heat pump. The payback time for the investment is expected to be less than three years.

SuPrHeat – Sustainable process heating with high-temperature heat pumps using natural refrigerants (Financed by EUDP; Project leader and partners: Teknologisk Institut (Leader), DTU Mekanik, Victor A/S, GEA Bock, Hamburg Vacuum, CS Techcom ApS, Spirax-Sarco, Alfa Laval Corporate AB, Fuchs Lubricants Denmark, VIEGAND & MAAGØE ApS, GEA Process Engineering, ARLA FOODS AMBA, DANISH CROWN A/S, DUPONT NUTRITION BIOSCIENCES ApS, Harboes Bryggeri., Project period: 2020-2024), **Subtask2, Novel Heat Pumps**

The project aims at developing three high-temperature heat pump systems for process heat supply at temperatures of up to 200 °C. The three systems are based on steam (water), hydrocarbons, and CO_2 as working fluids, and they are optimized for different industrial applications. The technologies are supplementing each other, and altogether this heat pump portfolio implies the potential to cover all kinds of process heat demands up to 200 °C at highest efficiencies. Thereby, the technologies enable electrification and decarbonization of a wide share of the process heat demand of the industry and constitute a key-technology for reaching the Danish climate targets, especially when considering the increasing share of renewables in the power generation and the respective potentials through sector coupling.

EUDP 2016 Mixed refrigerant heat pumps/cooling systems (MIREHP) (Financed by EUDP; Project leader and partners: Teknologisk Institut (Leader), SAUTER BUILDING CONTROL DENMARK ApS, Alfa Laval Aalborg A/S, DANARCTICA ApS, Technical University of Denmark; Project period: 2016-2019), **Subtask 2, Novel Heat Pumps**

The project will develop knowledge to find the best suitable zeotropic refrigerant mixtures for heat pumps and cooling systems, as well as to build a pilot setup for conducting functional analysis to validate the theoretical foundation and gain experience regarding an optimal setup configuration and control. Focus will be on controlling the temperature glide for both the evaporator and condenser.

SmartHeat (EU Frame progrma; Project leader and partners: Suntherm ApS (Leader); Project period: 2016), **Subtask 2, Storage**

SUNTHERM has developed a Worlds first 25 kWh thermal storage compact battery, based on salt hydrate dissolved in mineral oil that enables up to 25 hours of heat displacement (patent pending). SmartHeat consists of: Smart heating and heat storage, provided by a 25 kWh thermal battery (60 × 60 × 200 cm), coupled to a module of cloud-based management with an online control unit for real-time control over heat management, acting as a buffer in the grid. Although, the current project mainly focus on household applications, the knowledge and expertise that have been obtained in the project can be implemented in industrial applications. Therefore, the project fits well into subtask 2.

ELEC-TO-HEAT (Financed by EUDP; Project leader and partners: Suntherm ApS (Leader), DTU BYG, Teknologisk Institut; Project period: 2017-2020), **Subtask 2, Storage**

The objective of the project is to further develop and improve the main components of the first generation SUNTHERM domestic heating system. This will be accomplished in part by identifying and optimizing the operation of the heat pump and performance of the heat storage unit - e.g. identifying optimal conditions for operation with regards operating temperatures, storage capacity, domestic hot water needs etc. The identified improvements will then be implemented, tested and verified so that theory is translated into measureable, real-world results and knowledge. Although, the current project mainly focus on household applications, the knowledge and expertise that will be obtained in the project can be used for implementation of these technologies in industrial application to optimize excess heat usage. Therefore, the project fits well into subtask 2.

Compact thermochemical storage for residential heating systems using green electricity, **,** (Financed by Elforsk; Project leader and partners: Technical University of Denmark (Department of Energy Conversion and Storage (Leader), Department of Mechanical Engineering), Suntherm ApS, MT Stålindustri; Project period: 2020-2023), **Subtask 2, Storage**

The project aims at further development of SUNTHERM SmartHeat, an intelligent residential heating system, by developing a new heat battery based on thermochemical storage. The new type of heat battery works with the absorption/desorption of ammonia from salts, giving heat storage density 40 times larger than water and 10 times larger than the best phase change materials (PCM). The idea is to develop a cost-effective heat battery optimized explicitly for decentralized heat storage in private homes, which can be combined with heat pump outdoor unit. The objective is to design, build and test a prototype of a thermochemical heat battery. Although, the current project mainly focus on household applications, the knowledge and expertise that have been obtained in the project can be implemented in industrial applications. Therefore, the project fits well into subtask 2.

Small-scale CSP — Numerical and experimental analysis of a novel thermal energy storage for a small-scale concentrated solar power plant (Financed by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Individual Fellow; Project leader and partners: DTU Mechanical Engineering (Leader), Heliac ApS; Alfa Laval AB; IMDEA Energy Institute; Project period: 2018-2020)**, Subtask 2, Storage**

The project addresses the analysis of a cost-effective concentrated solar energy driven cogeneration system with thermal energy storage. To this end, the project addresses the investigation of a novel micro-structured polymer foil-based concentrated solar power system and investigations of a novel packed-bed rock thermal energy storage system. The micro-structured polymer foil-based concentrated solar power system has the advantages of a low installation cost and a low operation and maintenance cost. The thermal energy storage is based on a packed-bed rock with heat storage charging and discharging using evaporation and condensation of heat transfer fluid. Although, the current project mainly focus on solar power plant application, the knowledge and expertise that will be obtained in the project can be used for implementation of these technologies in industrial application to optimize excess heat usage.

Sun-Charge — Solar thermal power with evaporation based storage for on-demand charging of electrical vehicles (Financed by EUDP; Project leader and partners: Heliac ApS, (Leader), DTU Mechanical Engineering, Siemens A/S, Aalborg CSP; Project period: 2018-2021)**, Subtask 2, Storage**

The aim of this project is to design, develop and demonstrate a cost-effective solar thermal energy based solution where combined electricity and district heating can be made on-demand at a cost between 20-30 øre/kWh in Denmark. This will be done by increasing the operation temperature of current polymer foil based solar plants to 350 °C using thermal oil in combination with a novel low-cost stone based thermal storage with evaporation based heat extraction feeding a steam generator. The low cost will allow for feasible seasonal storage. The novel thermal storage solution allows for fast discharging, thereby enabling fast charging of electric vehicles without the need for grid reinforcement. Although, the current project mainly focus on electric vehicle applications, the knowledge and expertise that will be obtained in the project can be used for implementation of these technologies in industrial application to optimize excess heat usage.

Two-phase expansion in turbo-expanders for organic Rankine cycle power systems (The project is part of a collaboration between Technical University of Denmark and Technion (Israel Institute of Technology) within the framework of the EuroTech alliance for science and technology; Project period: 2020-2023), **Subtask 2, Low-temperature Power Production and Solar**

The aim of the project is to perform a comprehensive design of low-cost and efficient turbo-expanders for organic Rankine cycle systems working with a two-phase mixture. The optimization procedure will therefore take into account thermodynamic and aerodynamic issues as well as manufacturing process feasibility and cost. An additional contribution regarding the design of suitable materials for two-phase expanders blading will be given by the research carried out at Technion on this topic.

Waste heat recovery on Liquefied and natural gas-fueled (Financed by The Danish Maritime Fund, Orients Fund, European Union's Horizon 2020 research and innovation programme, Project leader and partners: Technical University of Denmark, MAN Diesel & Turbo, Alfa Laval, Fjord Line and Lloyd's Register Marine; Project period: 2017- 2020)**, Subtask 2, Low-temperature Power Production and Solar**

The project WHR Maritime aims at deriving guidelines with respect to the optimal utilization of waste heat sources on-board and identifying the optimal design, implementation and control of ORC units at LNG-fuelled ships. The project will include numerical analyses as well as a demonstration of a prototype ORC unit in the workshop at Mechanical Engineering department, Technical University of Denmark. The possibilities for an on-board demonstration on a vessel will also be evaluated. Although, the current project mainly focus utilization of waste heat sources on ships, the knowledge and expertise that will be obtained in the project can be used for implementation of these technologies in industrial application to optimize excess heat usage.

Design of innovative low-cost expanders for organic Rankine cycle power systems (The project is carried out within the frames of the EuroTech agreement on joint-supervision of doctoral candidates in collaboration between Thecnical University of Denmark and the Laboratory for Applied Mechanical Design, EPFL, École Polytechnique Fédérale de Lausanne, Switzerland; Project period: 2017- 2020)**, subtask 2, Low-temperature Power Production and Solar**

The project conducts a comprehensive analysis of the relation of manufacturing effort and performance of centrifugal impellers using an integrated design approach. The objective is to provide the scientific basis needed for the accurate and cost effective design of turbo expanders for ORC systems. In addition, the project will provide a comprehensive cost, volume, mass and performance prediction model for small-scale turbo-generator assemblies for how to fit in the machine on board a mobile application case.

Experimental analysis of non-saturated two-phase heat transfer in plate heat exchangers for organic Rankine cycle applications (Project period: 2020-2022), **subtask 2, Low-temperature Power Production and Solar**

The project will conduct a comprehensive experimental analysis of the heat transfer and pressure drop characteristics of non-saturated two-phase heat transfer and vapour single-phase heat transfer in plate heat exchangers using both the pure working fluids and zeotropic mixtures. The objective is to provide the scientific basis needed for the accurate design and performance prediction of evaporators and condensers for ORC systems. In addition, the guidelines will be provided on how to select the inlet and outlet conditions of the evaporator and condenser in terms of subcooling/superheating degree in order to maximize the performance of the ORC system.

PowerUp (Financed by EUDP; Project leader and partners: WEEL & SANDVIG ENERGI OG PROCESINNOVATION ApS (Leader), Akzo Nobel Salt; Arla Foods; Equinor Refining, Denmark and Nordic Sugar, Nykøbing; Project period: 2019-2020)**, Subtask 2, Novel Heat pump**

This project aims at discovering the economic potential for electrification of the industrial sector by means of extensive high-temperature electro-mechanical heat pumping. The goal is to reduce CO2 emissions significantly by substituting heat or steam, generated from combustion of fuels, by upgrading excess heat in temperature by heat pumping.

Projects for Subtask 3

Here is the list and brief descriptions of relevant projects from Denmark in Subtask 3 provided to IETS (for further information on projects, please contact the Danish Authors):

Smart management system for Industrial heat pumps (Financed by Elforsk; Project leader and partners: SC Solution Aps (Leader), Nordisk Energirådgivning; Project period: 2019-2020), **Subtask 3**

Heat pumps do not use the management options available today, which can help ensure an energy cost efficient operation, where it interacts with the company's energy systems and the electricity grid. The project will gather relevant parameters that affect the heat pump's energy cost and thereby control the heat pump better economically and energy efficiently.

ACT-ORC - Advanced Control of Organic Rankine Cycle Systems for Increased Efficiency of Heavy-Duty Transport (Financed by European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement (EurotechPstdoc); Project leader and partners: Technical University of Denmark (DTU), Technical University of Munich (TUM) and Scania; Project period: 2020-2022)**, Subtask 3**

The aim of the project is to develop suitable advanced controllers for organic Rankine cycle units recovering waste heat from heavy-duty vehicles. The goal is to maximize the net power output of the organic Rankine cycle unit while guaranteeing safe operation over realistic driving conditions. The control concepts will be proven both numerically and experimentally on a 3-kW organic Rankine cycle test rig under construction at the Technical University of Denmark. The test rig has the uniqueness of using a variable-speed axial-flow turbine and of being able to exploit different heat sources from the main diesel engine, i.e. the exhaust gas tailpipe, the cooling water loop and the charge air leaving the turbocharger. The knowledge and expertise, which will be obtained during the project, can be used to integrate low temperature excess heat from industrial sites into supply systems, optimize excess heat usage systems.

TB/RH/CD/AB

Projects for Subtask 4

Here is the list and brief descriptions of relevant projects from Denmark in Subtask 4 provided to IETS (for further information on projects, please contact the Danish Authors):

PowerUp (Financed by EUDP; Project leader and partners: WEEL & SANDVIG ENERGI OG PROCESINNOVATION ApS (Leader), Akzo Nobel Salt; Arla Foods; Equinor Refining, Denmark and Nordic Sugar, Nykøbing; Project period: 2019-2020)**, Subtask 4**

This project aims at discovering the economic potential for electrification of the industrial sector by means of extensive high-temperature electro-mechanical heat pumping. The goal is to reduce CO2 emissions significantly by substituting heat or steam, generated from combustion of fuels, by upgrading excess heat in temperature by heat pumping.

Projects for Subtask 5

Project Name: SuPrHeat – Sustainable process heating with high-temperature heat pumps using natural refrigerants

Summary

This project aims at developing three high-temperature heat pump systems for process heat supply at temperatures of up to 200 °C. The three systems are based on steam (water), hydrocarbons, and CO_2 as working fluids, and they are optimized for different industrial applications. The technologies are supplementing each other, and altogether this heat pump portfolio implies the potential to cover all kinds of process heat demands up to 200 °C at highest efficiencies. Thereby, the technologies enable electrification and decarbonization of a wide share of the process heat demand of the industry and constitute a key-technology for reaching the Danish climate targets, especially when considering the increasing share of renewables in the power generation and the respective potentials through sector coupling.

Introduction

Heat pumps are proven technologies for electricity-based heat supply by recovering excess heat from the same processes. Thereby, heat pumps yield considerable increases in overall energy efficiency, a reduction of primary energy consumption and an additional reduction of CO_2 emissions by replacement of combustion-based processes.

However, despite the considerable potential for contributing to the political and industrial ambitions in reducing GHG emissions with heat pumps for the range between 100 °C to 200 °C, there is a lack of suitable heat pump technologies for supply temperatures above 90 °C. Exploiting this potential requires technologies that reach highest performances in a variety of applications.

Reaching highest performances does however require an application-specific design of the heat pump system. Therefore, this project aims to develop a modular and flexibly combinable heat pump portfolio, which comprises a wide range of solutions with the possibility for further application-specific modifications.

TB/RH/CD/AB

Aims and objectives

This project aims at developing and demonstrating high-temperature heat pump solutions, which are able to supply heat at up to 200 °C. The developed technologies imply the potential to have an immediate impact on the electrification and decarbonization of industrial heat supply and thereby constitute a direct contribution to fulfilling the Danish climate ambitions.

The main objectives of the project are:

- Development of a modular and flexibly combinable concept of high-temperature heat pump technologies, which is able to cover the wide majority of industrial process heat demands at up to 200 °C
- Enabling a higher number of HTHP installations by advanced methods for process integration:
    - Development of advanced methods to find the optimal integration of heat pumps in existing process facilities under consideration of technical and non-technical aspects
    - Integration of high-temperature heat pumps in new process equipment for heat-intensive processes incl. a reassessment of process parameters and a simultaneous optimization with the heat pump
- Development, function and performance testing and demonstration in operating environment at end-user of the high-performance heat pump portfolio in three demonstration racks with a heating capacity of each 500 kW
- Increasing the awareness for the potential of high-temperature heat pump solutions with respect to decarbonizing the process heat demand of industries

Content and methodology

During the project, a high-temperature heat pump solutions, which are able to supply heat at up to 200 °C, will be developed and demonstrated at the end users. The solutions will operate at highest efficiencies and enable an electrification and decarbonization of a considerable share of the industrial process heat demand of the Danish industry. The technology development and demonstration activities will be supplemented with activities that develop advanced methods for supporting the optimal integration process of high-temperature heat pumps. These activities comprise methods for finding the most optimal placement under consideration of various technical and non-technical aspects and the development of conversion strategies to facilitate and support the transition towards electricity-based process heat supply.

Based on pre-studies, a combination of three technologies was identified as a promising portfolio of high-temperature heat pump technologies with the potential to provide high-performance solutions for the majority of the industrial process heat demand at up to 200 °C. These three technologies comprise the natural working fluids water (R718), hydrocarbons, and CO_2 (R744).

The project comprises various R&D activities on component and system level, and it aims at demonstrating the three technologies, each with a heat supply capacity of 500 kW in an operational environment. Within the first step, a concept will be developed, which provides a basis for the most optimal exploitation of the technical potential of the technology portfolio. This will comprise the derivation working domains for each technology as well as the identification of promising combinations of the different technologies.

The technology developments will accordingly be based on the identified working domains and comprise the following activities:

- *System design and component development:* the system design comprises the cycle design and optimization, and it constitutes the basis of the component development. The components will to a large extent be based on existing components, which will be modified with respect to utilization at higher temperatures and pressures.

- System testing at a variety of operating conditions and potentially required modifications: the systems will be assembled and tested with respect to function and performance at a variety of operating conditions. The tests will focus on demonstrating the performance and include a close monitoring of the most critical components

- Long-term testing at end-users: the demonstrations racks will be demonstrated at large scale end-users representing the food industry with respect to long-term performance

Results

The project has been started in 09/2020 and will continue up to 08/2024. There is no results available yet, however the expected outcome of the project will be providing:

- Novel high-temperature heat pump solutions that will prove technically and economically feasible
- Novel methods for industrial process integration, which will allow complete integration of heat demands, excess heat and electric power for heat pumping
- Mapping of industrial heating technology which may be equipped with high-temperature heat pumps for direct unit-operation electrification
- Component designs that will allow high efficiency and feasibility of high temperature heat pumps

Conclusion

The project will approach the potential and the challenges related to making industry's high temperature demands part of the green transition of society by allowing high-efficient electrification in terms of heat pumps also for these demanding conditions. Heat pumps are commercially mature for conventional purposes and heat demands, while supply temperatures at levels higher than 100 °C targeted in this project, are only available to limited extent.

Answers to the questions related to the subtask

1.5. Subtask 5

- Actual demonstration of industrial heat pumps for high temperature applications in collaboration between industry, equipment suppliers, process experts and research institutions

- Development of novel process integration approaches accounting for cycle, refrigerant, process integration and electrification options

Project Name: Digital Twin for large scales heat pump and refrigeration systems

Summary

Heat pump and refrigeration systems are key components of future energy systems. The systems are receiving a growing attention, especially with respect to integration into smart grids and sector coupling. Digitalizing heat pump and refrigeration systems and integrating them in the Internet of Things (IoT) imply the possibility to improve the long-term performance of the systems as well as using them for sector coupling by operating them flexibly according to demand side management. However, an integration into the IoT does require an enhanced knowledge about the system during operation, which may be difficult and costly to determine when using conventional approaches.
So called digital twins imply the possibility to analyse existing measurements and to obtain insights about the system during operation by numerical modelling. Digital twins are a virtual representation of a physical system in the form of numerical models, which are constantly adapting to the current operating conditions. Such models are adapted by measuring selected operating parameters and by enabling the possibility of identifying inherent operating conditions of the entire system. This implies different services with a range of benefits, such as:

- Advanced system monitoring
- Optimized system operation through:
  - Optimized system control with a possibility to operate the system flexibly
  - Optimized operation scheduling under consideration of periods for production, supply of flexibility, predictive maintenance, and other purposes
- Fault detection and diagnosis

This project aims at reducing the modelling effort associated with digital twins by developing reusable, modular and self-learning models as well as advanced methods for analysing the system, which are specifically developed for the intended services. This enables not only an efficient implementation process and thereby decreased investment cost of digital twins, but it also enables an enhanced exploitation of the system potentials.
The project targets two technological implementation areas; large-scale heat pump systems primarily for district heating and supermarket refrigeration systems. The Digital Twin technology will be demonstrated within both areas. One case study will take place in the supermarket refrigeration field and two case studies will focus on heat pumps for district heating at two different areas of Denmark.

Introduction

Large-scale heat pumps provide the possibility to exploit natural and excess heat sources for heating purposes using electricity and driving power. Refrigeration systems are well established systems for large-scale cooling applications, such as in supermarket. Both systems are based on the same thermodynamic cycle, which makes it a promising approach to look at the optimization of these

systems in a combined way. The systems are receiving a growing attention, especially with respect to integration into smart grids and sector coupling. Digitalizing heat pump and refrigeration systems and integrating them in the Internet of Things (IoT) implies the possibility to improve the long-term performance of the systems, as well as using them for sector coupling by operating them flexibly according to demand side management. An integration into the IoT does however require an increased knowledge about the system during operation, which may be difficult and costly to determine using conventional approaches.
So-called digital twins imply the possibility to analyse the existing measurements and obtain insights about the system during operation by use of advanced computer models.

Therefore, This project aims at developing methods to reduce the modelling effort associated with obtaining digital twins and the requirements for specific services.

Aims and objectives

The project aims at reducing the modelling effort associated with digital twins by developing reusable, modular and self-learning models as well as advanced methods for analysing the system, which are specifically developed for the intended services. This enables not only an efficient implementation process and thereby decreased investment cost of digital twins, but it also enables an enhanced exploitation of the system potentials.
The project targets two technological implementation areas; large-scale heat pump systems primarily for district heating and supermarket refrigeration systems. The Digital Twin technology will be demonstrated within both areas. One case study will take place in the supermarket refrigeration field and two case studies will focus on heat pumps for district heating at two different areas of Denmark.

The main objectives of the project are:

- The role of digitalization in the energy transition
- Digital twins for large-scale heat pump and refrigeration systems
- The potential of digital twins for heat pump and refrigeration systems
- Bringing digital twins into application and demonstrating the benefits

Content and methodology

Digital twins are a set of numerical models, which mimic the real, physical system. They are continuously adapting to the current status of the system to ensure an ongoing accuracy with regard to the system status. The numerical models may be based on different approaches and differ in complexity. Currently, the creation of digital twins is associated with a considerable effort, which prevents their wide adoption in this kind of applications. Therefore, this project focuses on decreasing the effort for creating digital twins by developing service-oriented models, which fulfill the intended services while being modular, reusable, and with limited complexity.

The operating plant is producing much data, which is mainly used to ensure the provision of the key services such as heating and cooling. However, through sophisticated analyses, it is intended to valorize this data in order to provide additional or improved services. This is done by analysing the data in various ways, including the direct analysis as well as a model-based analysis. In addition, the use of numerical models allows for the consideration of external data forecasts such as weather data, and consumer profiles of variable electricity tariffs.

TB/RH/CD/AB

The data analyses create additional insights about the system and how to use it, which is the basis for exploiting the technical potential most optimally with respect to various services:

Advanced system monitoring:
In a first step, it is important to monitor the system and gain insights, which may not be concluded directly from measurements. This implies:

- Analysis of functionality and performance of systems and components
- Performance benchmarking of systems and components
- Soft sensors

These services enable conclusions about the system performance during operation and enable the possibility of comparison to simulated benchmarks and other systems. In addition, parameters may be estimated which enables redundancy of sensors by soft sensors as well as estimation of parameters, which are difficult to measure.

Fault detection and diagnosis:
The continuous data analysis enables the possibility to detect and analyse fault mechanisms at an early stage and to take respective precautions.

- Fault mechanism monitoring including early stage warning and predictive maintenance
- Model-based interpretation of system alerts

Optimized system operation:
Limited knowledge about the system and its status leads to conservative and sub-optimal operating set-points. Based on the numerical models, set-points for optimal operation may be determined under consideration of various aspects such as supply of heating and cooling, variable electricity tariffs, and required downtime. Possible services comprise:

- Continuous set-point tuning
- Scheduling of production times and downtime.

The optimized system operation has a direct feedback on the plant operation and thereby a direct feedback on the creation of new measurement data.

The digital twins may be located and structured on different levels. This comprises data handling on sensor and actuator level, system level, or cloud level.

There are various projects that are related to the suggested project and to some extent correspond to the state of the art that is to be extended. In the following, an overview of the relations to the most relevant R&D projects is presented.

Experimental development of electric heat pumps in the Greater Copenhagen DH system (SVAF) - phase 2 (Status: Ongoing, Period 2016-2022)

The aim of the project was to accelerate the use of large electric heat pumps for district heating through industrial cooperation, research and experimental development. Large heatpumps (HPs) face a number of barriers preventing large-scale introduction. One is the feasibility of the investments – in particular in areas with low alternative heat costs as in Greater Copenhagen Area (GCA). Also lack of knowledge and operation experiences, especially use of natural refrigerants (required by Danish law) and supplying heat above 70 degrees, are important. This project addressed the main barriers in order to accelerate the use of HPs for system integration with improved cost efficiency and with potential for scaling up concepts to 50-100 MW. The overall project consists of three phases. The purpose of the present Phase 2 project was to develop and demonstrate two electric 5 MW HPs based on:

- Sea water and waste water

The SVAF project aimed, besides the analysis of seawater and sewage water as heat sources, to develop methods for improving the thermodynamic performance by set point optimization and to develop simple fault detection algorithms. Both approaches were based on data that was generated with the plant before the commencement of commercial operation.
This approach requires to conduct a series of experiments with the existing plant, which is both time consuming and only possible during times without commercial operation. The conclusions that may be drawn from this approach are limited to the conditions of the components and the system at the point of the experiments.

The results indicated that a model-based approach would be more practicable. Therefore, the project comprised first studies in which a none-adaptive steady state model was used. These activities indicated that the numerical models should become easier to implement, numerically more robust and imply an adapting character in order to fully exploit the potentials of online set point tuning. The suggested project aims to reduce both the modelling effort while increasing the level of detail to being suitable for the specific services.

Energylab Nordhavn – New urban energy infrastructures (Status: Finished, Period 2015-2019)
The Energylab Nordhavn project demonstrated various energy technologies for applications in highly integrated energy systems. It was formed as a triple helix bringing together academia, industry, utilities, and local government to pursue solutions for the design and operation of a cost – efficient and integrated energy system for the future – all based on living lab in Nordhavn in Copenhagen and the innovation power that such a physically integrated place can offer. The project builds on Copenhagen power grid and district heating network, but also ventures far into the built environment and private dwelling to co-model and co-simulate these in order to unlock their flexibility potential. Among others, the project comprised the analysis of a large-scale heat pump (FlexHeat) that is able to provide frequency power reserves as well as a supermarket refrigeration system that is able to supply district heating as a secondary service. The project demonstrated the general suitability of these technologies to provide several services including the socioeconomic benefits.

The project did however also indicate that exploiting the potential of supplying several services by one unit requires sophisticated control structures. This aspect will be covered by the suggested project, with a focus on optimal operation with respect to multiple services.

Results
The project is an interdisciplinary R&D project involving eight partners, which cover the entire range from research and development to final applications. The project is structured in nine work packages and runs four years from February 2020 until January 2024. There is still no results from the project available, however all the activities, news and reports related to project can be found in Digital Twins (digitaltwins4hprs.dk)

TB/RH/CD/AB

Conclusion

The project will develop reusable, modular and self-learning models and advanced methods for analysing the system to reduce the modelling effort associated with obtaining digital twins and the requirements for specific services. This enables not only an efficient implementation process and thereby decreased investment cost of digital twins but also an enhanced exploitation of the system's potentials

Answers to the questions related to the subtask

1.5.Subtask 5

- Advanced dynamic models
- Integration with/intophysicalplant in operation
- Combination with useof data-driven models

- Provision of services as:
  - Sectorcoupling
  - Optimizedoperation
  - Predictivemaintenance
  - Faultdetection

TB/RH/CD/AB

Project Name: THERMCYC - Advanced thermodynamic cycles utilising low-temperature heat sources

Summary

The project aimed at solutions for thermal plants, for power generation, heat pumping and cooling by use of low value sources as waste heat and renewable sources at high efficiency. The project developed the design of both processes and working fluids to achieve significant energy savings. Energy sources at a low temperature level are available from a variety of sources ranging from waste heat from ships, industry and refrigeration plants, to renewable energy in the form of biomass, geothermal and solar.

There is significant potential for improving the use of these sources in developing new cycles based on new multi-component fluid mixtures. These improvements will not only increase the efficiency of today's technology, but they will also make it possible to use low-temperature sources which, due to lack of technical feasibility or economy is not used today.

The overall outcome of the project provided a scientific basis for choosing the future use of low-temperature resources in Denmark. This may contribute significantly to the development of the future society using no fossil resources, but large amounts of fluctuating renewable energy.

As a part of the results of this project presented in (High performance heat pump systems; PhD Thesis; Benjamin Zühlsdorf, 2019), it is indicated that there is a potential for considerable improvements in both thermodynamic and economic performance, if the working fluid is selected among pure and zeotropic working fluids for the specific application. Zeotropic mixtures have the potential to increase the performance of heat pumps considerably, especially in applications in which the heat source and heat sink experience temperature glides. The performance improvement potentials are case specific and exploiting these potentials requires a sophisticated procedure for selecting the working fluid and designing the heat pump cycle. The interdependencies between the working fluid, the components and the system were studied for enabling a system design for fully exploiting the peculiarities of zeotropic mixtures. Exergy analysis revealed that the majority of the performance improvement resulted from matching the temperature profiles of the working fluid and the secondary fluids. Without major adjustments of the cycle, increases in the coefficient of performance (COP) of more than 30 % were obtained for a beneficial fluid choice. In addition, different technologies were studied with respect to their techno-economic feasibility for the supply of process heat at temperatures above 150 °C. A reversed Brayton cycle using R-744 and a cascade system with a multi-stage cycle using R-718 showed high potentials in applications with large temperature glides. The reversed Brayton cycle was cost-effective and less complex, while the cascade system had a higher flexibility with respect to the process integration. Both systems were found to be promising for extending the possible supply temperatures to 300 °C or higher, while the economic potentials were highest when combined with own renewable electricity generation.

TB/RH/CD/AB

Introduction

Low-temperature heat sources are available in many applications, ranging from waste heat from marine diesel engines, industries and refrigeration plants to biomass, geothermal and solar heat sources. There is a great potential for enhancing the utilization of these heat sources by novel cycle design and use of multi-component working fluids. These advancements will not only improve the performance of existing technologies, but also enable the utilization of low-temperature heat sources, which are currently not utilized due to technical or economical infeasibility.

Aims and objectives

The project aimed at devising innovative thermodynamic cycles that utilize low-temperature heat sources with performances superior to state-of-the-art. It addressed advancements in cycle and component design, and the use of new multi-component working fluids. Power, heat pump and cooling plants were considered, with focus on efficient power production and heat pump applications that utilize intermittent power sources efficiently. The goal was to derive solutions that result in significant energy savings in Danish industry and marine vessel consumption.

Content and methodology

The THERMCYC project was an interdisciplinary research project focusing on the analysis of using working fluid mixtures in heat pump and power cycles. The outcome of project should not only improve the performance of existing technologies, they should also enable the utilization of low-temperature heat sources that are not used currently due to technical or economical infeasibility. Examples of possible, new applications include power production using small-scale solar and biomass, and geothermal heat sources. Moreover, high-efficient heat pumps can be developed. By providing the scientific basis needed for implementation of technologies utilizing low-temperature energy sources in Denmark, the project contributed to the development of the future society with no consumption of fossil fuels and high shares of intermittent, renewable energy sources

The project comprised analysis on cycle level for both heat pump and power cycles, component analyses of compression and expansion machines and heat exchangers as well as computer aided molecular design of working fluids. the characteristics of working fluids using Multi-criteria database search and Molecular Design principles to generate, test and evaluate promising pure component/mixture candidate as process fluids to help optimize cycle design and performance were studied.

The main work packages of THERMCYC were:

- Thermodynamic cycles for pure and mixed working fluids
    - Power cycles, e.g., Organic Rankine Cycles (ORC)
    - Heat pump cycles

- Component design
    - Heat exchangers
    - Compression and expansion machines

- Novel working fluids
    - Computer aided molecular design (CAMD)
    - Property uncertainty analysis

- Experimental validation
    - Experimental validation of suggested concepts

- Implementation in industry
    - Analysis of the business potential of the developed solutions
    - Conduction of four case studies to numerically analyse and demonstrate the practicability of the suggested solutions

Results

The project developed solutions that result in significant energy savings and reduction of CO_2 emission in Danish industry and marine vessel consumption. A lot of reports, PhD thesis, and conference and peer review papers published in high impact journals should be mentioned as part of the outcomes of the project. The papers cover wide range of topics such as:

- Design and optimization of components such as compressors, heat exchangers, turbines for heat pumps and organic Rankine cycles
- Design and optimization of a novel cycles
- Optimization of pure and mixed working fluids for heat pumps and organic Rankine cycles
- Guidelines for optimal selection of working fluid for heat pumps organic Rankine cycles

A complete list of reports, presentations and publications is available on https://www.thermcyc.mek.dtu.dk/publications

Conclusion

The work covered a development of a systematic approach to the design and optimization of components and cycles as well as the working medium in the power, heat pump and cooling plants. The focus was efficient power production and heat pump applications that utilize intermittent power sources efficiently.

This project leaded the way to innovative thermal system for electricity generation, heat pumping and cooling by utilization of low value sources, at efficiencies that surpasses today's level significantly. The project developed software tools to support the systematic selection of working fluids.

As a part of the results of this project presented in (High performance heat pump systems; PhD Thesis; Benjamin Zühlsdorf, 2019), it is indicated that there is a potential for considerable improvements in both thermodynamic and economic performance, if the working fluid is selected among pure and zeotropic working fluids for the specific application. Zeotropic mixtures have the potential to increase the performance of heat pumps considerably, especially in applications in which the heat source and heat sink experience temperature glides. The exergy analysis revealed that the majority of the performance improvement resulted from matching the temperature profiles of the working fluid and the secondary fluids. Without major adjustments of the cycle, increases in the coefficient of performance (COP) of more than 30 % were obtained for a beneficial fluid choice.

Answers to the questions related to the subtask

1.5.Subtask 5

- Collaboration between industry, equipment suppliers, process experts and research institutions
- Focus on heat utilization for both power and heat pumping
- Focus on power cycles, heat pump cycles, working fluids including mixtures, and components – both machinery and heat exchangers