Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Final Report

Part 1

Prepared by
Members of Annex 35/13

Contents

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Executive Summary

Prepared by
Members of Annex 35/13

Contents

1 Introduction

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important global challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. In particular industrial heat pumps (IHPs) offer various opportunities to all types of manufacturing processes and operations. IHPs are using waste process heat as the heat source, deliver heat at higher temperature for use in industrial processes, heating or preheating, or for space heating and cooling in industry. They can significantly reduce fossil fuel consumption and greenhouse gas emissions in drying, washing, evaporation and distillation processes in a variety of applications. Industries that can benefit from this technology include food and beverage processing, forest products, textiles, and chemicals.

The introduction of heat pumps with operating temperature below 100 °C is in many cases considered to be easy, however, higher temperature application still require additional R&D activities for the development of high temperature heat pumps, integration of heat pumps into industrial processes and development of high temperature, environmentally sound refrigerants.

In this context, the IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry

The Annex 35/13 started on 01. April 2010 and expired on 30. April 2014 with 15 participating organisations from Austria, Canada, Denmark, France, Germany (Operating Agent) Japan, The Netherlands, South Korea and Sweden.

The Annex comprised an overview in the participating countries of the industrial energy situation and use, the state of the art and R&D projects in heat pumping and process technologies and its applications, as well as analysing business cases on the decision-making process in existing and new applications and in the wider application of industrial heat pumping technologies. The annex has been subdivided in the following tasks:

- Task 1: Market overview, barriers for application
- Task 2: Modeling calculation and economic models
- Task 3: Technology
- Task 4: Application and monitoring
- Task 5: Communication.

2 Market overview, barriers for applications

The Task 1 Report summarized the present energy situation in general and the industrial energy use and related heat pump market subdivided into participating countries. Based upon these findings focus will be given to further work to meet the challenges for the wider application of industrial heat pumping technologies.
Although heat pumps for the industrial use became available on the markets in the participating countries in recent years, just very few carried out applications can be found. To distinguish the reasons for this situation, application barriers were also a part of the survey in Task 1:

- Lack of knowledge:

  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers and decision makers in the industry have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.

- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump.

- Long payback periods:

  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.

- High temperature application
  From the technical point of view one barrier can be identified regarding to the temperature limits of most commercially available heat pumping units. Many applications are limited to heat sink temperatures below 65°C the theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps including refrigerants for heat sink temperatures up to and higher than 100°C.

  The barriers can be solved, as shown in the results of the Annex: short payback periods are possible (less than 2 years), high reduction of CO_2-emissionen (in some cases more than 50 %), temperatures higher than 100°°C are possible, supply temperatures < 100 °C are standard.

3 Modelling calculations and economic models

The Task 2 Report intended to outline how the integration of IHP in processes is supported by computer software, i.e. by modeling.

In order to 'update' the Annex 21 screening program in the sense of a 'modern' development taking the original goals into account a proposal has been made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.
- Development of a heat pump data base to be used within the simultaneous optimization. Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

This concept of integrating a heat pump into a process is 'below' the sophisticated methods given by H.E. Becker [Methodology and Thermo-Economic Optimization For Integration of Industrial Heat Pumps, THÈSE NO 5341 (2012), ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, Suisse, 2012]. Presently it is impossible to state whether such a development is unprecedented, relevant and needed.

The scoping analysis of existing models shows that the difference between 'pure' pinch models and sophisticated mathematical optimization models has been bridged in modern software tools. Regarding the integration of heat pumps into a process, codes like OSMOSE or CERES (amongst may be others) look promising.

Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

The goals of Task 2 should be carefully reconsidered if a "new Task 2" team should be constituted. The State of the Art as well as industrial needs of research organizations, large companies as well as of energy consultants should be critically reviewed. We conclude that the application of general optimization methods is limited to a fairly small number of research groups and highly specialized groups within large companies. Energy consultants probably will prefer pinch analysis type models. In the whole context we consider the thesis of H.C. Becker (directed by F. Maréchal) as key reference due to the systematic methodology, based on pinch analysis and process integration techniques, to integrate heat pumps into industrial processes

4 Technology

The scope of the Task 3 Report was to identify in the industrial sector appropriate heat pumps as a technology of using waste heat effectively and for meeting future industrial and environmental requirements.

Commercially available heat pumps can supply heat only up to 100 °C. As industrial waste heat, available at low-temperatures, represents about 25 % of the total energy used by the manufacturing industry, R&D work has to be focused on high-temperature heat pumps able to recover heat at relatively low temperatures, generally between 5°C and 35°C for hot water supply, hot air supply, heating of circulating hot water and steam generation at temperatures up and higher than 100 °C.

Some development of the industrial heat pump using R-134a, R-245fa, R-717, R-744, hydro carbons, etc. has been made recently. However, except for R-744 and the flammables R-717 and HCs which are natural refrigerants with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Refrigerant	**Chemical formula**	**GWP**	**Flammability**	**T_c °C**	**p_c M Pa**	**NBP °C**
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3CH2CH2CH2CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

5 Applications and monitoring

The **Task 4 Report** focused on operating experiences and energy effects of representative industrial heat pump implementations, in particular field tests and case studies.

Industrial heat pumps are a class of active heat-recovery equipment that allows the temperature of a waste-heat stream to be increased to a higher, more useful temperature. Consequently, heat pumps can facilitate energy savings when conventional passive-heat recovery is not possible

The economics of an installation depends on how the heat pump is applied in the process. Identification of feasible installation alternatives for the heat pump is therefore of crucial importance. Consideration of fundamental criteria taking into account both heat pump and process characteristics, are useful. The initial procedure should identify a few possible installation alternatives, so the detailed project calculations can concentrate on a limited number of options.

The commercially available heat pump types each have different operating characteristics and different possible operating temperature ranges. These ranges overlap for some types. Thus, for a particular application, several possible heat pump types often exist. Technical, economic, ecological and practical process criteria determine the best suited type. For all types, the payback period is directly proportional to installation costs, so it is important to investigate possibilities for decreasing these costs for any heat pump installation.

The survey with a total of 150 projects and case studies has tried to present good examples of heat-pump technology and its application in industrial processes, field tests and commercial applications along with an analysis of operating data, when available, in accordance with the annex definition of industrial heat pumps, used for heating, ventilation, air-conditioning, hot water supply, heating, drying, dehumidification and other purposes.

6 Final Conclusions and future actions

The IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

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The programme and work has been mainly concentrated on the collection of statistical energy and environmental data and information related to industry as well as the present status of R&D and the application of heat pumps in industry. In total **39 R&D projects and 115 applications** of heat pumps in industry, in particular the use of waste process heat as the heat source, have been presented and analyzed by the participating countries.

It has been shown that in many companies and especially in SMEs, only very little and aggregated information on the actual thermal energy consumption is available and disaggregated data such as consumption of individual processes and subprocesses therefore has either to be estimated or determined by costly and time-consuming measurements, which often requires the integration of several processes at different temperature levels and with different operating time schedules. The exploitation of existing heat recovery potentials often requires the integration of several processes at different temperature levels and with different operating time schedules. Different technologies available for heat supply have to be combined in order to obtain optimum solutions.

Basis for the modeling calculation and economic models activities (Task 2) has been the update of the IHP screening program, to determine how industrial heat pumps could be used in different applications, developed and presented in "Annex 21 - Global Environmental Benefits of Industrial Heat Pumps (1992 -1996)".

The IHP screening program has been analyzed and converted from an outdated Visual Basic version to the latest Visual Basic version employing the .NET framework. This new, converted version would in principle be ready for any modifications, updates of data and models as well as for extensions. However, during the execution of Task 2 it became obvious that the authors consider this approach as a dead-end and the screening program as obsolete. Since 1997 no further work on this program has been done and the authors decline any further developments. We simply noticed that the formulation of the corresponding item in the legal text did not take this situation into account. However, parts of the screening program, for instance the database, could be easily extracted and modernized for other purposes.

Although the Annex has been prolonged by one year, mainly because of missing results from Task 2, nearly none of the deliveries could be finished as foreseen, due to the fact that most participants are not concerned directly with modeling and software aspects and a large underestimation of the wide range of software tools with their very different scopes.

Taking into account the results of the annex with detailed information on statistical data, R&D results and case studies, a possible follow-up annex should be concentrated on a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept should be:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
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Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

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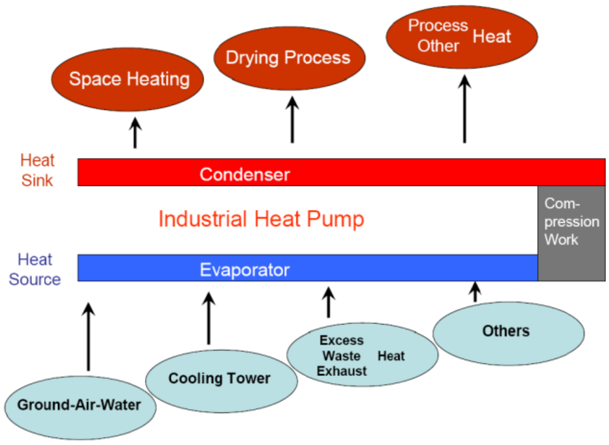
Policy Paper

Prepared by
Members of Annex 35/13

Application of Industrial Heat Pumps

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important global challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy. While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Industrial heat pumps (IHP) are active heat-recovery devices that increase the temperature of waste heat in an industrial process to a higher temperature to be used in the same process or another adjacent process or heat demand



Annex 35 / 13

The IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

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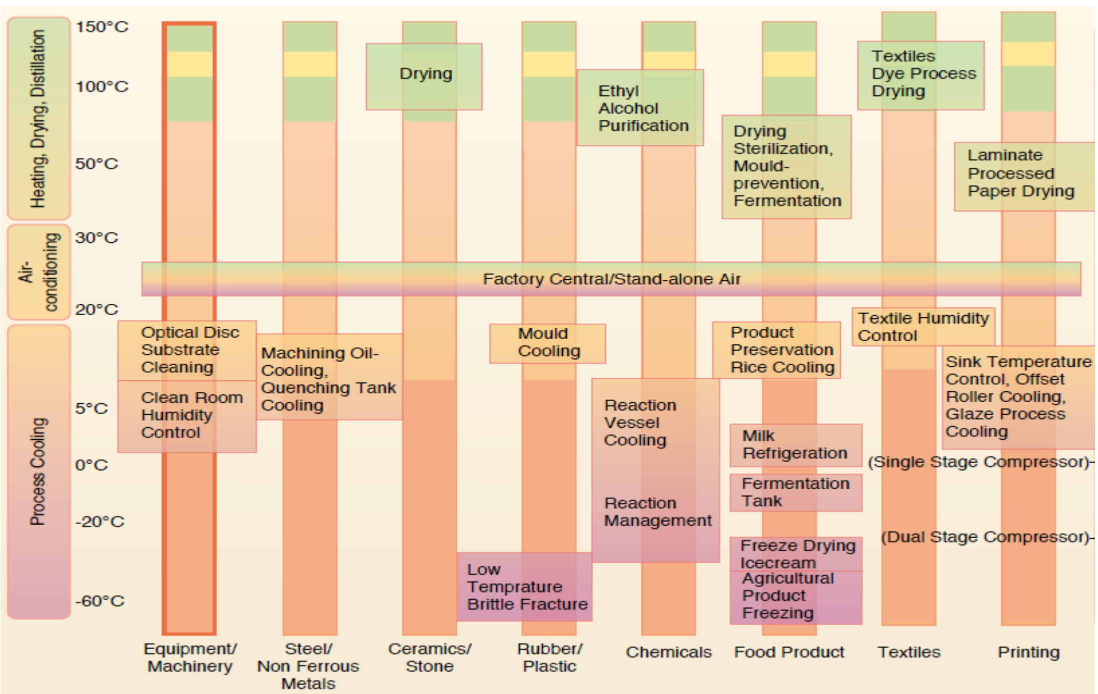
Industrial Heat Pump Applications



Barriers for application and solutions

Heat pumps for the industrial use are available on the markets in the participating countries in recent years, just very few carried out applications can be found. To distinguish the reasons were a part of the survey in the annex:

- Lack of knowledge:
  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers and decision makers in the industry have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.
- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump
- Long payback periods:
  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.
- High temperature application
  Many applications are limited to heat sink temperatures below 65°C. The theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps including refrigerants for heat sink temperatures up to and higher than 100°C.

The barriers can be solved, as shown in the results of the Annex: short payback periods are possible (less than 2 years), high reduction of CO_2-emissionen (in some cases more than 50%), temperatures higher than 100°°C are possible, supply temperatures < 100°C are standard.

The integration of industrial heat pumps into processes

The methods of integration IHPs in processes range from applying rules by hand to far advanced mathematical optimization and are discussed in the literature. The Task 2 Report outlines specifically how the integration of IHPs in processes is supported by computer software, i.e. by modeling.

In order to 'update' the Annex 21 screening program in the sense of a modern development retaining the original goals, a proposal has been made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

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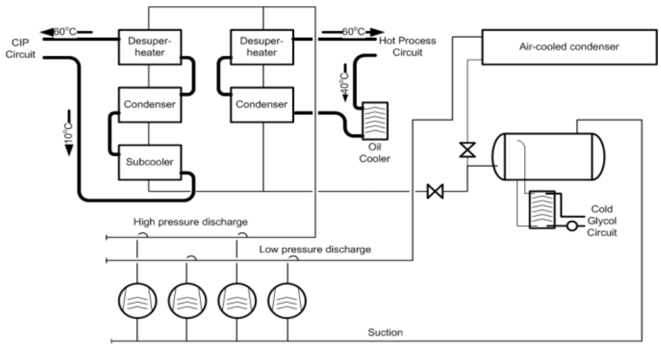
This concept of integrating a heat pump into a process is 'below' sophisticated mathematical optimization models and could therefore be considered as an **add-on** to the widely used programs based on pinch analysis enhancing their capabilities.

Examples of existing Installations

Heat pump in Food and Beverage industry - Combine heating and cooling in chocolate manufacturing (UK)

The chocolate manufacturing process also requires cooling capacity for certain steps of the process. These simultaneous demands for cooling capacity and heating capacity allowed the replacement of the heating and the cooling system by a combined cooling and heating installation. The idea was to install a Single Screw compressor Heat Pump combining Heating and cooling.



The Heat source consists in cooling process glycol from 5°C down to 0°C this evaporates Ammonia at -5°C and the heat pump lifts it to 61°C in one stage for heating. Process water is finally heated from 10°C to 60°C.

Based on the clients previously measured heating and cooling load profiles the analysis showed that to meet the projected hot water heating demands from the 'Total Loss' and Closed Loop' circuits, the selected heat pump compressors would have to produce 1.25 MW of high grade heat. To achieve this demand the equipment selected offers 914 kW of refrigeration capacity with an absorbed power rating of 346 kW. The combined heating and cooling COP, COP_{hc}, is calculated to be a modest 6.25. For an uplift of 17 K in discharge pressure the increase in absorbed power was 108 kW boosting the COP_{hi} to an impressive 11.57.

The initial thinking for the customer was to get a 90°C hot water heat pump. Indeed, some application demand required 90°C. However the total demand for this temperature level was around 10% of the whole hot water consumption. Designing a heat pump installation for such temperature would not be interesting in terms of performances and efficiencies. It was decided to install the heat pump producing 60°C hot water. When the small amount of 90°C water is required, the incremental heat is supplied now by a small gas boiler heating up the water from 60°C up to 90°C.

In parallel, other alternatives for the heating were assessed like a central gas fired boiler, combined heat power or geothermal heat pump. Qualitative and quantitative assessments (cost, required existing installation upgrade, future site growth…) defined that the best alternative solution for this project was the heat pump. So a correct analysis and understanding of the real need for the installation allow installing the right answer to the real Nestle needs.

Nestlé can save an estimated £143,000 per year (166,000 € per year) in heating costs, and around 120,000 kg in carbon emissions by using a Star Neatpump. Despite the new refrigeration plant providing both heating and cooling, it consumes £120,000 (140,000 €) less electricity per year than the previous cooling only plant.

Another impact of the complete project (combined heating and cooling, additional gas boiler for the 90°C water peak demand, etc.) decreased the total water consumption from 52,000 m^3/day down to 34,000 m^3/day.

The Nestlé system recently won the Industrial and Commercial Project of the Year title at the 2010 RAC awards.

Hybrid heat pump at Arla Arinco (Denmark)

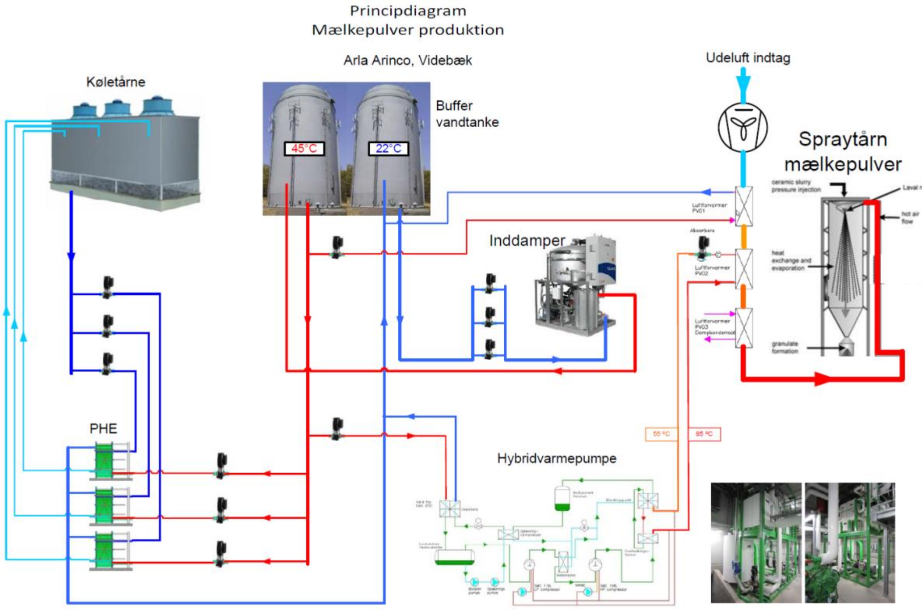
A heat pump of 1.25 MW was installed utilizing energy from 40° C cooling water – energy that was discharged to the environment prior to this project. The installed heat pump preheats drying air for milk powder to around 80° C through a water circuit.

The heat pump is installed in an application where ambient air is heated to 150 °C for drying milk powder. Previously this was done by a natural gas boiler. During the project the philosophy was to:

1. Minimize the energy demand
2. Incorporate direct heat exchangers as far as possible
3. Consider whether a heat pump is the best solution for the remaining energy demand.

The type of the heat pump is a Hybrid (compression/absorption) with the refrigerant NH_3/H_2O with a capacity of 1.25 MW.

Following these steps it became obvious that the best solution would be a heat pump only doing part of the heating towards 150 °C. It was also noticed that pre heating of the ambient air was possible through direct heat exchanging utilizing cooling water from an evaporator. The installation was thus changed to consist of three stages where the first is preheating to 40 °C using cooling water, second stage is heating from 40-80 °C using the heat pump – also recovering heat from the cooling water and third stage is heating from 80-150 °C using the existing gas boiler. Due to fluctuations in cooling and heating demands, two buffer tanks have been installed eliminating variations in the cooling system and ensuring steady conditions for the heat pump.



With a COP of 4.6 the heat pump approximately halves the energy cost compared to natural gas that is replaced. A high number of annual operation hours (around 7,400), ensures a considerable reduction in energy expenses. The analysis throughout the project also led to other energy reductions as well as direct pre heating of ambient air, thus the project as a whole caused substantial savings making this approach very profitable. Energy savings represent a tradable value in the Danish system for energy reductions. Because of the considerable amount of energy savings in this particular case, around half of the investment was financed through this value leading to a simple payback time of around 1.5 years and being very profitable from a life time perspective.

Another conclusion from the project is that engineering, design, construction, commissioning and operation of a heat pump plant of this size is comparable to that of industrial refrigeration plants.

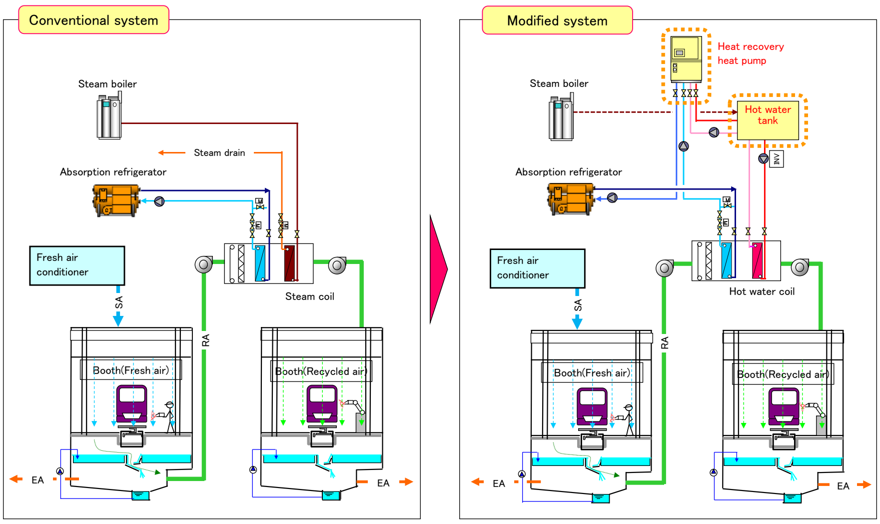
Adoption of Heat Pump Technology in a Painting Process at an Automobile Factory (Japan)

In a painting facility of an automobile factory, a great deal of energy is consumed by heating and cooling processes, the power supply, system controls, lighting, and so on. Generally, most primary energy sources are gas and electricity. Most heating and cooling needs in a painting process are supplied by direct gas combustion, steam, hot water, and chilled water generated by a refrigerator, most of the primary energy for which is gas. In terms of energy efficiency ratio, electrical energy was believed to be lower in energy efficiency than gas energy, because electrical energy uses only around 40 % of input energy while gas energy is able to use almost 100 % of direct gas combustion. However, heat pump technology has greatly improved, and the energy efficiency ratio is increasing accordingly, so highly efficient heat pumps have been introduced also into industrial processes in recent years.

There are three main advantages which we can gain from heat pump technology. The first is the heat recovery system, the second is efficient heat source equipment, and the third is simultaneous usage of cooling and heating, which is believed to be the most efficient usage. Simultaneous usage of heating and cooling can be applied to processes of pretreatment/electro-deposition, booth/working area air conditioning, and waterborne flash-off equipment. Hence, adoption of heat pump technology in this equipment is considered. The highest effect from adoption of heat pump technology in these cases is in booth recycled air conditioning and waterborne flash-off equipment.

Conventionally, the heat source system of a recycled air conditioner in the paint booth consists of a gas absorption refrigerator and a boiler. The recycled air conditioner was cooled by the gas absorption refrigerator, and reheated by boiler steam. In the meantime, the heat recovery heat pump enables us to supply both the heat for cooling and reheating concurrently. This modified system is provided to ensure system reliability and lower carbon emissions by utilizing existing equipment, such as the gas absorption refrigerator and the boiler, and also for backup purposes.

The heat pump makes it possible for the system to reduce running costs by about 63 %, to reduce CO_2 emissions by about 47 % per month, and to reduce primary energy consumption by about 49 % per month as compared with the conventional boiler. Consequently, the pay-back period would be estimated at 3～4 years.

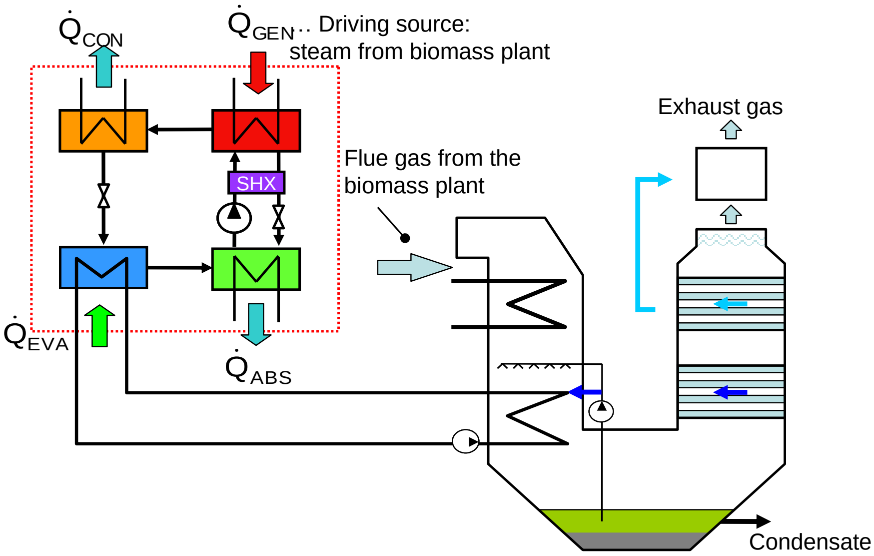


Absorption heat pump for flue gas condensation in a biomass plant

Schweighofer Fibre GmbH in Hallein (Austria) is a woodworking industrial company and part of the Austrian family enterprise Schweighofer Holzindustrie. Their core business is the production of high-quality cellulose and bioenergy from the raw material wood by an efficient and environmentally-friendly use. A biomass power plant including a steam generator supplies the in-house steam grid and covers the company's energy demand at the site. The capacity of this cogeneration plant, which is fired by 77 % of external wood and 23 % of in-house remants, amounts to about 5 MW_{el} and 30 MW_{th}. Beside the in-house power supply of Schweighofer Fibre GmbH the biomass plant also delivers electricity for about 15,000 households and heat for the local district heating grid.

The AHP offers the possibility to use the condensation heat of the flue gas by upgrading its temperature level, even thou the return flow temperature of the existing district heating grid is higher than the dew point temperature of the flue gas. At evaporating temperatures of the AHP lower than 50 °C the flue gas gets sub cooled below the dew point temperature. Hence, the temperature level of the condensation heat of the flue gas is lifted up to a useful level for the district heating. Otherwise, the condensation heat of the flue gas could not be used and would be dissipated to the ambient.

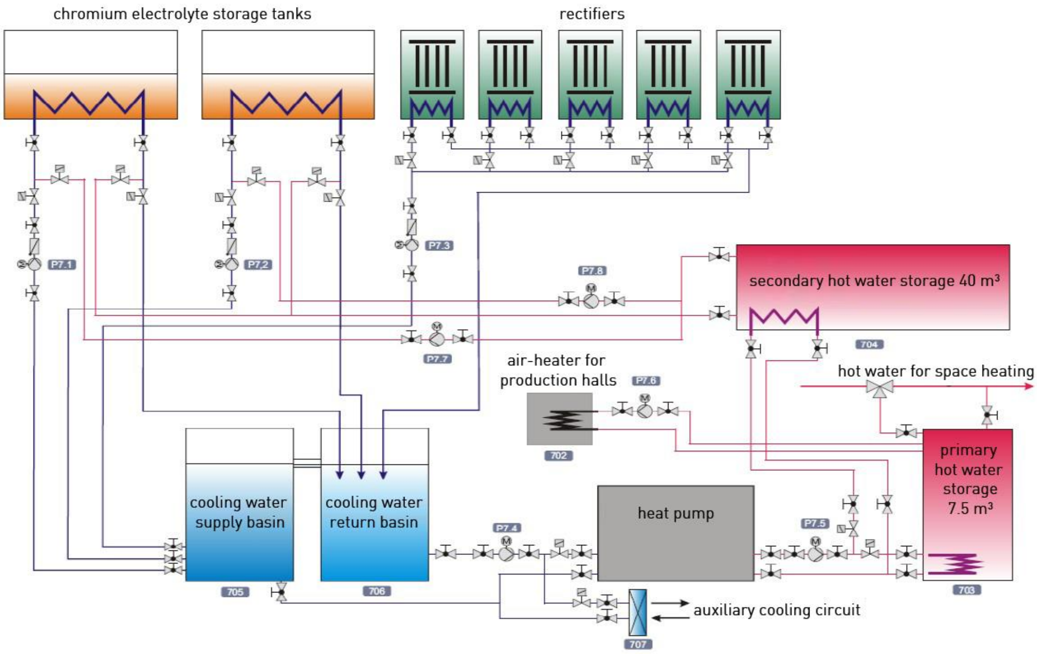
The applied AHP is a single-stage Water/LiBr absorption heat pump with a solution heat exchanger (SHX) and a heating capacity of ca. 7.5 MW. The driving source of the AHP is steam from the biomass heating plant at ca. 165 °C. According to the existing monitoring system the AHP operates with a seasonal performance factor (SPF) of about 1.6. Due to the high efficiency and the high operating hours of the AHP this industrial heat pump application enables a significant fuel and emission reduction. Additionally to the ecological advantages this application offers an economical benefit for the operator of the plant.



The benefits are energy savings of ca. 15,000 MWh/a, a higher performance and no vapour discharge system is required.

Metal processing (Germany)

Thoma Metallveredelung GmbH is an electroplating company that offers a various surface treatments. The company is a very active driver for the rational use of energy in the electroplating industry. In a research project funded by Deutsche Bundesstiftung Umwelt (DBU) a concept for a new energy saving hard chromium line was developed. Chromium plating is a technique of electroplating a thin layer of chrome onto metal objects. This is done by immersing the objects into a bath of chromium electrolyte. By applying direct electric current, chromium is plated out on the object´s surface. Usually only 20 % of the electric energy are used to create the chromium coating. The remaining 80 % are converted into waste heat. As the electroplating process is very temperature-sensitive cooling has to be applied to the electroplating bath.



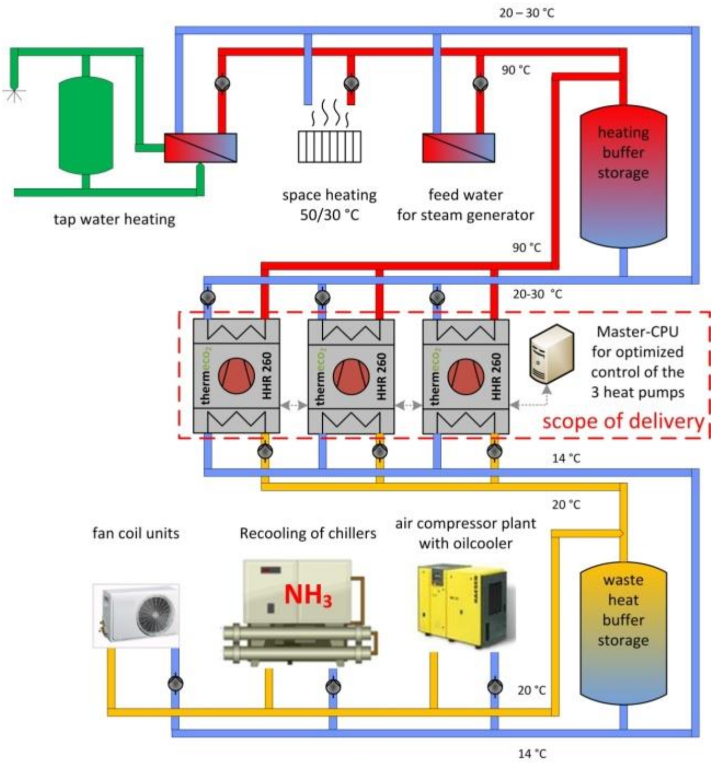
The company has increased the over-all efficiency of this process to more than 90 % by improving the electroplating process and integrating a heat pump to reuse the generated waste heat. By increasing the current density from 50 A/dm² to 90 A/dm² the efficiency of the electroplating process could be increased to 24 %. To maintain a good surface quality the temperature of the bath had to be raised to more than 60 °C. As the process still produces a large heat surplus, the electrolyte tanks as well as the current rectifiers are cooled by a water circuit. The cooling water returns to a collecting basin at a temperature of 60 °C. Because in the company there is no heat needed at 60 °C, the cooling water basin serves a heat source for a heat pump. The heat pump has a heating capacity of 143 kW and produces hot water at 75 to 80 °C. At this temperature level hot water is used for space heating and to supply others baths of the coating line. A 7.5 m³ storage serves as a buffer for space heating. Due to higher heating loads the process heat storage has a larger volume of 40 m³. Both heating and cooling system are operated bivalent. In case of a malfunction of the heat pump a groundwater well serves a heat sink for the cooling water, while an oil-fired heater covers the heating demand. The heat pump system covers 50 % of the heat demand and saves 150,000 l oil per year. Another positive effect of the new hard chromium line is significant process improvements. The coating hardness could be increased by 10%, while the plating rate could be increased by 80 %. For planning and implementation of the project experts from different engineering disciplines had to work together. The coordination of this work took a lot more effort than expected before. Nevertheless Thoma Metallveredelung GmbH is very satisfied with the result and plans to install similar heat recovery systems in their other coating lines. Furthermore the whole system was designed using standard components. In this way other electroplating companies can adapt the system without infringing property rights.

Slaughter House in Zurich (Switzerland)

In 2011, a new thermeco$_2$ heat pump system for hot water generation and heating was put into operation in the slaughterhouse Zurich. With a capacity of 800 kW, the plant is the largest ever built in Switzerland. The thermeco$_2$ machines deliver the required 90 °C with better COPs compared to other refrigerants. The heat pump system is built up of 3 heat pumps thermeco$_2$ HHR 260.

The heat pump uses waste heat of an existing Ammonia refrigeration machine, an oilcooled air compressor plant and the installed fan-coil units as heat source. For this reason the heat is collected in a waste heat buffer storage connected with the heat pump evaporators. Because of the closed waste water circulating loop no special measures to avoid corrosion are necessary.

The warm side of the heat pumps is connected with a hot water buffer storage. The consumer (warm water for slaughtering and cleaning purposes, feed water for a steam generator and the heating system) are provided from this buffer storage using their consumer pumps tailored to the particular demand.



Because of the extremely low space requirement, this large heat pump system could be installed in a container system on the roof of the slaughterhouse in a short distance to urban residential development. Only authorized personal has access to the container and CO_2 sensors have been installed that activate an alarm when healthy concentration levels are exceeded.

All of the thermal energy for the slaughterhouse Zurich was previously provided with steam boilers. The customer's decision for a high temperature heat pump system with CO_2 as a refrigerant on this scale had several reasons. The efficiency advantages of the high temperature heat pump system clearly have priority. Running this heat pump plant the city of Zurich, represented by the Umwelt- und Gesundheitsschutz Zürich (UGZ) and the Elektrizitätswerk Zürich (ewz) as Contractor make an important contribution towards the "2000 Watt Society" of the city of Zurich. In the calculated overall balance of the slaughterhouse, CO_2 emissions can be reduced by approx. 30 %. By using the heat pump system, 2,590 MWh from fossil fuels can be saved per year, representing an annual reduction in CO_2 emissions of 510 tonnes.

R&D high temperature heat pumps

EDF France in cooperation with industry is working on the development of high temperature industrial heat pumps with new working fluids to reach temperatures higher than 100 °C:

Alter ECO Project

This project includes the development and industrial testing of HPs capable of operating at 140 °C in condensation mode, equipped with scroll compressors and working with a new blend.

Publication: Experimental results of a newly developed very high temperature industrial heat pump (140 °C) equipped with scroll compressors and working with a new blend refrigerants.

Technical specifications :

- Condensation temperature : 77 to 140 °C
- Evaporation temperature : 30 to 60 °C
- Compressors max power : 75 kWe
- Condenser max power : 200 kWt

The compressor power is 75 kW. The machine performances have been characterized to demonstrate the technical feasibility. For each evaporation temperature (from 35 to 60 °C by step of 5 °C), the condensation temperature is increased by step of 5 °C from 80 up to 140 °C.

Test campaigns over 1,000 hours were carried out in industrial-like conditions to demonstrate the reliability.

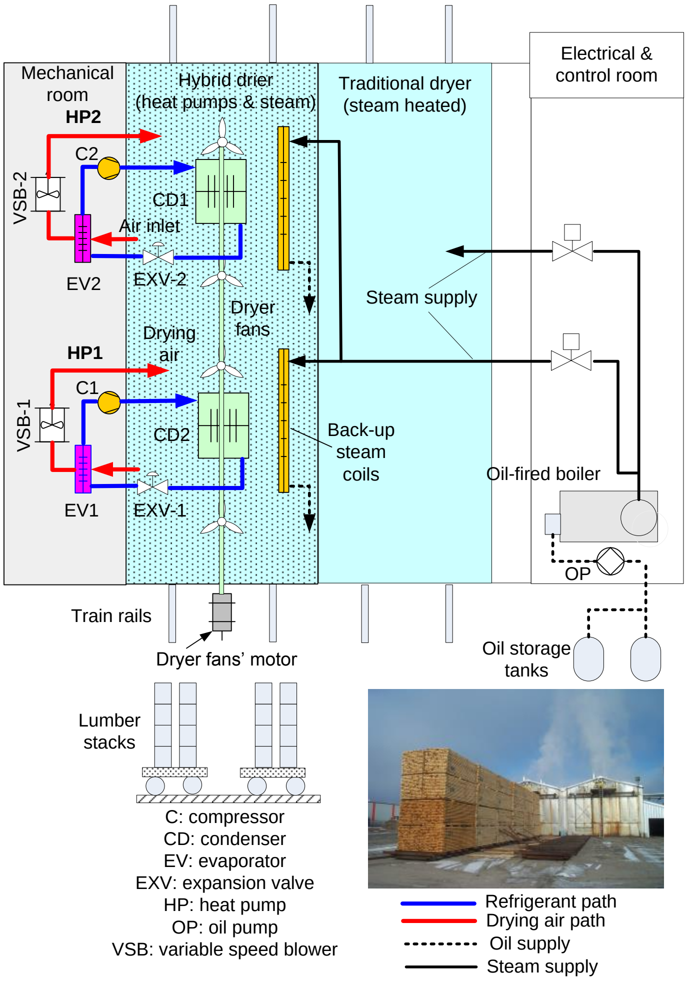
The efficiency of heat recovery up to 125 °C is demonstrated. Good performances are obtained. For higher temperatures, the technological feasibility is demonstrated but some further developments have to be carried out to increase the efficiency and the economic viability: 2 stage compressors (it is designed for a given pressure ratio), expansion valve, etc.

All this demonstrates the prototype reliability and the capacity to use this newly developed machine for industrial purposes.

PACO Project

Heat pump using water as a refrigerant is an interesting solution for waste heat recovery in industry. Water is nontoxic, non-ignitable and presents excellent thermodynamic properties, especially at high temperature. Water HP development is complex, notably due to water vapor compression. The compression ratio of centrifugal and lobe compressors is low. It prevents gas temperature from rising more than 20 °C. For now, the only technical solution able to overcome this drawback with moderate costs is to put two lobe compressors in series. However, theses compressors are less reliable than the others and their efficiency is low. Thus, the development of a novel water compressor is needed. Screw and centrifugal compressors on magnetic bearings seem to be the most promising technology. Discussions with the compressor manufacturers, and the numerical simulations show that the COP can be increased up to 80 % if such a compressor is integrated on a water heat pump. The price of this prototype compressor is very high, but it should decrease with the development of the market. Thus, the payoff would be guaranteed and the water heat pump would become an industrial reality.

High-temperature drying heat pump

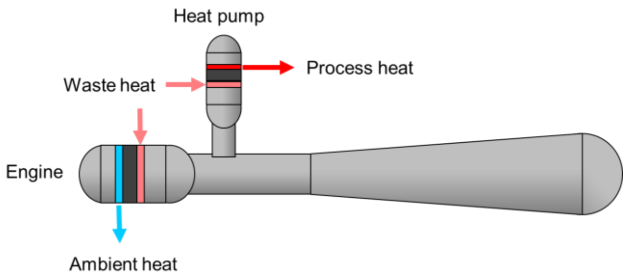


An industrial-scale, high-temperature heat pump-assisted dryer prototype, including one 354 m^3 forced-air wood dryer with steam heating coils and two high-temperature heat pumps (see Figure) has also been studied in Canada. Finished softwood lumber is produced in standard sizes, mostly for the construction industry. Softwood, such as pine, spruce and fir (coniferous species), is composed of vertical and horizontal fiber cells serving as a mechanical support and pathway for the movement of moisture. These species are generally dried at relatively high temperatures, but no higher than 115 °C, and thus high-temperature heat pumps coupled with convective dryers are required. An oil-fired boiler supplies steam for wood preheating and supplemental (back-up) heating during the subsequent drying steps. The dryer central fans force the circulation of the indoor drying air and periodically change their rotation sense to make more uniform and, thus, to improve the overall drying process and the wood final quality. Each heat pump includes a 65 kW (nominal electrical power input) compressor, an evaporator, a variable speed blower and electronic controls located in an adjacent mechanical room. Both remote condensers are installed inside the drying chamber. The high-temperature refrigerant (HFC-236fa) is a non-toxic and non-flammable fluid, having a relatively high critical temperature compared to the highest process temperatures. Expansion valves are controlled by microprocessor-based controllers that display set points and actual process temperatures. The industrial-scale prototype demonstrates that, as a clean energy technology compared with traditional heat-and-vent dryers, the high-temperature heat pump-assisted dryers offer very interesting benefits for drying resinous timber. Its actual energy consumption effectively is between 27.3% and 56.7% lower than the energy consumed during the conventional (steam) drying cycles, whereas the average reduction in specific energy costs, compared to the average costs of the Canadian conventional wood drying industry (2009), is of approximately 35 %.

Thermo Acoustic Heat Transformer

Thermo acoustic (TA) energy conversion can be used to convert heat to acoustic power (engine) and to use acoustic power to pump heat to higher temperature levels (heat pump). The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts.

Although the dynamics and working principles of TA systems are quite complex and involve many disciplines such as acoustics, thermodynamics, fluid dynamics, heat transfer, structural mechanics, and electrical machines, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology. When thermal energy is converted into acoustic energy, this is referred to as a Thermo acoustic (TA)-engine. In a TA-heat pump, the thermodynamic cycle is run in the re-verse way and heat is pumped from a low-temperature level to a high-temperature level by the acoustic power. This principle can be used to create a heat transformer, as shown below.



The TA-engine is located at the left side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump, located on top of the resonator. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site.

Basic characteristics of refrigerants suitable for high temperature heat pump

Some development of the industrial heat pump using R-134a, R-245fa, R-717, R-744, hydro carbons, etc. has been made recently. However, except for R-744 and the flammables R-717 and HCs which are natural refrigerants with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3CH2CH2CH2CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

Operating Agent: Annex 35/13 Application of industrial Heat Pumps

Information Centre on Heat Pumps and Refrigeration (IZW e.V.)

IZW is a German society for the promotion of research and development of heat pumps and refrigeration, to contribute to the reduction of the primary energy consumption and CO_2 emissions and the improvement of the energy-efficiency and environmental protection at the heat production, refrigeration and in the manufacturing industry.

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Members:

What is the IEA Heat Pump Programme?

The Programme is a non-profit organisation funded by its member countries. It is the foremost worldwide source of independent information and expertise on environmental and energy conservation benefits of heat pumping technologies.

What is the aim of the Heat Pump Programme?

The aim is to achieve widespread deployment of appropriate practical and reliable heat pumping technology systems that can save energy resources while helping to protect the environment.

Why is that important?

The world's energy and climate problems are well known. The buildings sector is responsible for a very considerable proportion of greenhouse gas emissions. Heat pumps are a key technology in the solution to break this trend.

What needs to be done?

By disseminating knowledge of heat pumps worldwide, we contribute to the battle against global warming. In order to increase the pace of development and deployment of heat pumps for buildings and industries, we need to increase R&D efforts for heat pumps, and we need to implement long-term policies for further deployment of heat pumps.

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Basics of Industrial Heat Pumps

Final Report

(Status: 01.09.2014)

Prepared by
Operating agent
IZW e.V.

Contents

1 Introduction

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy.

About 30 % of the global energy demand [IEA, 2013] and CO_2 emissions are attributable to industry, especially the big primary materials industries such as chemicals and petrochemicals, iron and steel, cement, paper and aluminium. Understanding how this energy is used, the national and international trends and the potential for efficiency gains, are crucial.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. The heat pump markets are currently growing at a steady pace, however, in many countries focused mainly on residential heat pumps for space heating and cooling as well as domestic hot water. Heat pumps for high temperature applications and industrial use have often been neglected, as the share of energy cost has been low for companies and thus investments to improve production normally have a much higher priority than investments in energy efficiency. Increased use of energy has, to some extent, been an indication of economic growth.

Industrial heat pumps (IHPs), however, offer various opportunities to all types of manufacturing processes and operations. Increased energy efficiency is certainly the IHPs most prominent benefit, but few companies have realized the untapped potential of IHPs in solving production and environmental problems. IHPs can offer the least-cost option in getting the bottlenecks out of production process to allow greater product throughput. In fact, IHPs may be an industrial facility's best way of significantly and cost-effectively reducing combustion related emissions [Leonardo, 2007].

Industrial heat pumps are using waste process heat as the heat source, deliver heat at higher temperature for use in industrial process heating or preheating, or for space heating and cooling in industry. They can significantly reduce fossil fuel consumption and greenhouse gas emissions in drying, washing, evaporation and distillation processes in a variety of applications as well as heating and cooling of industrial and commercial buildings. Industries that can benefit from this technology include food and beverage processing, forest products, textiles, and chemicals.

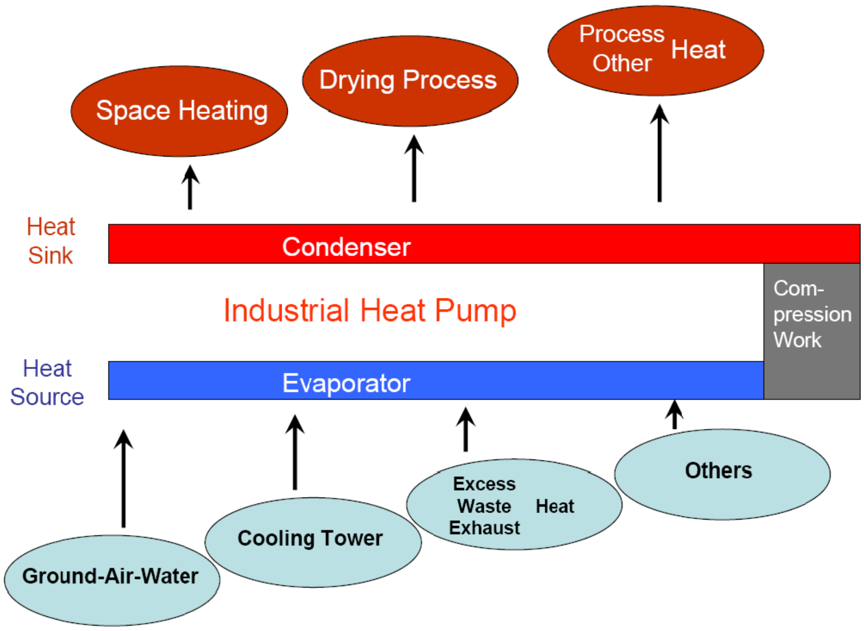

Figure 1-1: Heat sources and heat sinks in industrial heat pumps

While the residential market may be satisfied with standardized products and installations, most industrial heat pump applications need to be adapted to unique conditions. In addition a high level of expertise of heat pumps and processing is crucial.

Industrial heat pumps within this annex are defined as heat pumps in the medium and high power ranges which can be used for heat recovery and heat upgrading in industrial processes, but also for heating and cooling in industrial buildings.

Their potential for energy conservation and reduction of CO_2-emissions are enormous and at this moment not naturally a part of policy papers. The following problems and respective needs for research are related to the market introduction of IHPs:

- lack of refrigerants in the interesting temperature range
- lack of experimental and demonstration plants
- uncertainty by potential users as to HP reliability
- lack of necessary knowledge of heat pump technology and application by designers and consulting engineers.

On the other side, IHPs have the following advantages in comparison to heat pumps for space heating:

- high coefficient of performance (COP) due to low temperature lift and/or high temperature levels
- long annual operating time
- relatively low investment cost, due to large units and small distance between heat source and heat sink
- waste heat production and heat demand occur at the same time.

2 Physical principles

A heat pump is essentially a heat engine operating in reverse. Its principle is illustrated below.

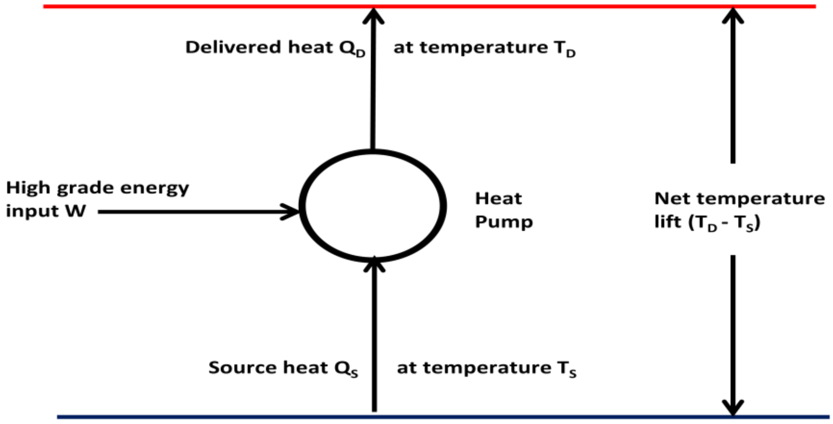

Figure 2-1: Heat pump principle

From the first law of thermodynamics, the amount of heat delivered Q_D at the higher temperature $T_D$is related to the amount of heat extracted Q_S at the low temperature T_S and the amount of high grade energy input W by the equation

$$Q_D = Q_S + W$$

Compared to heat pumps for space heating, using heat sources such as ground or water, IHPs often have the following advantages:

- high coefficient of performance due to low temperature lifts and/or high temperature levels;
- long annual operating times;
- relatively low investments cost, due to large units and small distances between heat source and heat sink;
- waste heat production and heat demand occur at the same time.

Despite these advantages, the number of heat pump installations in industry is almost negligible compared to those installed for space heating.

Note:
A coefficient of performance (COP) can be defined as

$$COP = \frac{Q_D}{W}$$

The Carnot coefficient of performance

$$COP_c = \frac{T_D}{T_D - T_S}$$

represents the upper theoretical value obtainable in a heat pump system.

In practice attainable coefficients of performance are significantly less than COP_c. Unfortunately, it is difficult to compare the COPs of different categories of IHP, which differ widely for equivalent economic performance. When comparing heat pump systems driven by different energy sources it is more appropriate to use the primary energy ratio (PER) defined as

$$PER = \frac{usefull\ heat\ delivered}{primary\ energy\ input}$$

The equation can be related to the coefficient of performance by the equation

$$PER = \eta \times COP$$

where η is the efficiency with which the primary energy input is converted into work up to the shaft of the compressor.

3 Heat pump technology

3.1 Criteria for possible heat pump applications

The first step in any possible IHP application is to identify technically feasible installation alternatives, and possibilities for their economic installation.

In simple operations, where the process in which the IHP will be used only consists of a few streams with obvious sink and source, the need for a thorough assessment is normally not necessary. In these cases, only the characteristics of the sink and source are of importance for the feasibility and selection of the IHP. The obvious parameters are:

- heat sink and source temperature;
- size (in terms of heat load) of the sink and source;
- physical parameters of the sink and source, such as phase and location

Industrial heat pumps are used in the power ranges of 50 – 150 kW and 150 to several MW.

The sink and source temperatures determine which IHP types can be used in a specific application. These types can be categorized in various ways, e.g. as mechanically- or heat-driven, compression or absorption, closed or open cycles.

3.2 Thermodynamic processes

The most important thermodynamic processes for industrial heat pumps are:

- closed compression cycle - electric driven or gas-engine driven
- mechanical (MVR) and thermal (TVR) vapour recompression
- sorption cycle
- absorption–compression cycle
- current developments, e. g. thermo acoustic, injections

and will be described in the next chapters.

3.2.1 Mechanical compression cycles

The principle of the simple closed compression cycle is shown below.

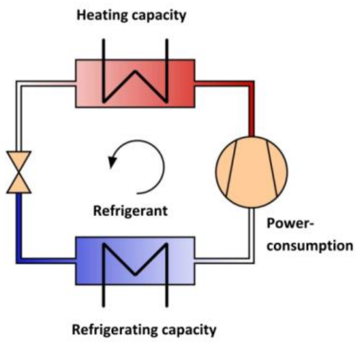

Figure 3-1: Closed compression cycle

Four different types of compressors are used in closed compression cycle heat pumps: Scroll, reciprocating, screw and turbo compressors.

Scroll compressors are used in small and medium heat pumps up to 100 kW heat output, reciprocating compressors in systems up to approximately 500 kW, screw compressors up to around 5 MW and turbo compressors in large systems above about 2 MW, as well as oil-free turbo compressors above 250 kW.

3.2.1.1 Vapour injection

In the economizer vapour injection (EVI) cycle, see figure below, a heat exchanger is used to provide additional sub-cooling to the refrigerant before it enters the evaporator. This sub-cooling process provides the increased capacity gain measured in the system. During the sub-cooling process, a certain amount of refrigerant is evaporated. This evaporated refrigerant is injected into the compressor and provides additional cooling at higher compression ratios, similar to liquid injection.

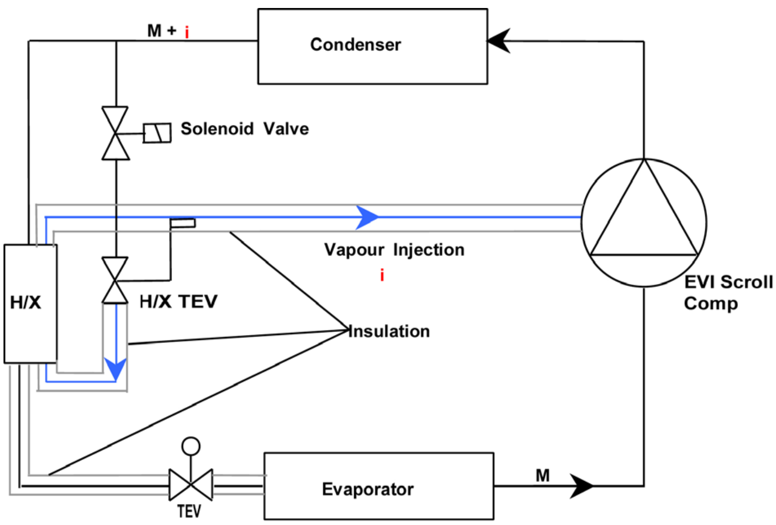

Figure 3-2: Vapour injection

3.2.2 Thermal compression cycles

3.2.2.1 Absorption heat pumps

Absorption heat pump cycles are based on the fact that the boiling point for a mixture is higher than the corresponding boiling point of a pure, volatile working fluid. Thus the working fluid must be a mixture consisting of a volatile component and a non-volatile one. The most common mixture in industrial applications is a lithium bromide solution in water ($LiBr/H_2O$) and ammonia water (NH_3/H_2O).

The fundamental absorption cycle has two possible configurations: absorption heat pump (AHP, Type I) and heat transformer (AHP, Type II), which are suitable for different purposes.

The difference between the cycles is the pressure level in the four main heat exchangers (evaporator, absorber, desorber and condenser), which influence the temperature levels of the heat flows.

The application of absorption cycles for high temperature heat recovery systems calls for the investigation of new working pairs. To qualify as a potential working pair, a mixture of two substances has to fulfil stringent requirements with respect to thermodynamic properties, corrosion and safety hazards like toxicity and inflammability.

Based on a thermodynamic analysis of an absorption heat pump cycle a systematic search for new working pairs has been required, e. g. investigation of organic compounds.

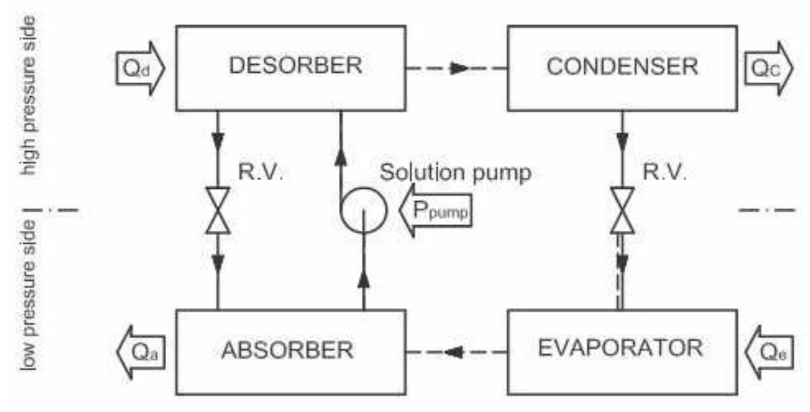

Figure 3-3: Absorption

3.2.2.2 Absorption-compression hybrid

The hybrid heat pump combines substantial parts of both absorption and compression machines - it utilizes a mixture of absorbent and refrigerant and a compressor as well. An important difference between hybrid and absorption cycle should be noticed - the absorber and desorber in the hybrid heat pump are placed in a reversed order than in the absorption machine, i.e. desorption in the hybrid cycle occurs under low temperatures and pressures and absorption under high temperatures and pressures.

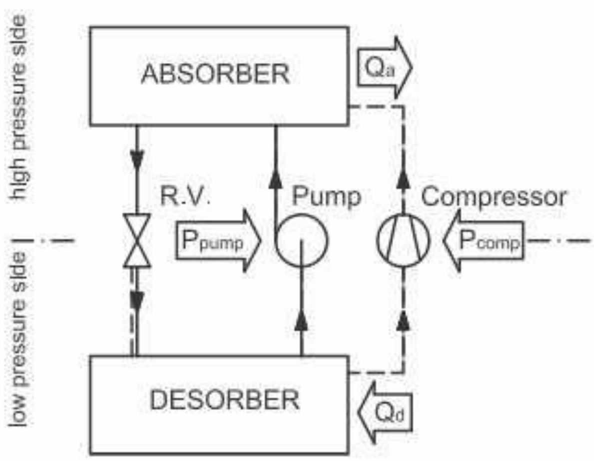

Figure 3-4: Absorption – compression hybrid

3.2.3 Mechanical vapour recompression (MVR)

Mechanical vapour recompression is the technique of increasing the pressure and thus also the temperature of waste gases, thereby allowing their heat to be re-used. The most common type of vapour compressed by MVR is steam, to which the figures below refer. There are several possible system configurations. The most common is a semi-open type in which the vapour is compressed directly (also referred to as a direct system). After compression, the vapour condenses in a heat exchanger where heat is delivered to the heat sink. This type of MVR system is very common in evaporation applications

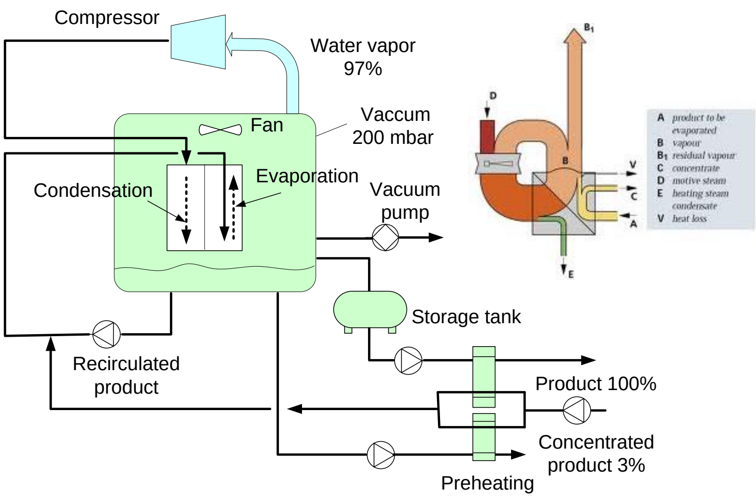

Figure 3-5: Mechanical vapor recompression [Bédard, 2002]

The other type of semi-open system lacks the condenser, but is equipped with an evaporator. This less usual configuration can be used to vaporize a process flow that is required at a higher temperature, with the aid of mechanical work and a heat source of lower temperature.

3.2.4 Thermal vapour recompression (TVR)

With the TVR type of system, heat pumping is achieved with the aid of an ejector and high pressure vapour. It is therefore often simply called an ejector. The principle is shown in the figure below. Unlike MVR system, a TVR heat pump is driven by heat, not mechanical energy. Thus, compared to an MVR system, it opens up new application areas, especially in situations where there is a large difference between fuel and electricity prices.

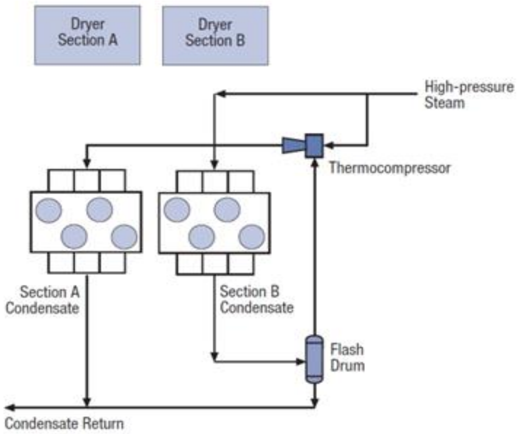

Figure 3-6: Thermal vapor recompression, Example from Japan

The TVR type is available in all industrial sizes. A common application area is evaporation units. The COP is defined as the relation between the heat of condensation of the vapour leaving the TVR and heat input with the motive vapour.

3.2.5 Thermo acoustic (TA)

The acoustic energy is subsequently being used in a TA-heat pump to upgrade waste heat to usable process heat at the required temperature. The picture below visualises the whole system. The TA-engine is located at the right side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site.

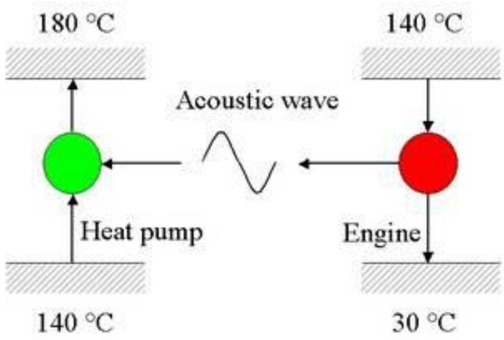

Figure 3-7: Thermo acoustic heat pump

3.3 Refrigerants suitable for high temperature heat pump

Many industrial processes have heating demands in the temperature range of 90-120 °C. At the same time, waste heat holding typically a temperature of 30-60 °C is available. Efficient heat pumping technologies are therefore attractive in order to reduce the specific energy consumption (kWh/product amount). The present, most common refrigerants, in particular HFCs are limited to heat distribution temperatures of around 80 °C. For temperature above 100 °C additional R&D is required.

Industrial heat pump using R-134a, R-245fa, R-717, R-744 and hydrocarbons (HC), etc. However, except for R-744 and the flammables R-717 and HCs, which are natural refrigerants with extremely low global warming potential (GWP.) HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the view-point of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Table 3-1: Refrigerants, considered to be suitable for IHPs

Refrigerant	**Chemical formula**	**GWP**	**Flammability**	**T_c °C**	**p_c M Pa**	**NBP °C**
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3-CH2-CH2-CH2-CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

4 Energetic and economic models

As a consequence of the first law of thermodynamics all energy that is put into a process will also, in a steady state situation, leave the process. The energy leaves the process in the shape of product, waste heat and other losses.

The temperature level of the waste heat is determined by process fundamentals and process equipment design, and is thus, for an existing plant, set. However the temperature level which the waste heat appears and can be used is determined by the design of the utility systems, i.e. cooling water and air. This essential difference is often overlooked when discussing waste heat utilization.

The amount and temperature level of the waste heat can be determined by process integration methods, e.g. pinch analyses. These methods are powerful tools and give a total picture of the situation at the plant including the possibilities for internal use of the heat.

There are several competing alternatives to utilize waste heat and it is normally not obvious which is the most favorable. The heat can internally be better used for heating purposes and in new or modified process parts. Heat pumping is also an alternative which today is common practice in some branches but has a large potential to grow in others. Another option is to use the heat for heating demands outside the plant in a district heating system.

To be able to increase the awareness of possibilities and to select between the alternatives, a high level of expertise for system design, process integration and planning is crucial. Design software on process integration and design plays an important role at this stage. However, this seemingly being a complex approach needing a lot of high level expertise, simple straight forward solutions on a small scale should not be overseen.

4.1 Pinch analysis

Pinch analysis is a methodology for minimising energy consumption of chemical processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimising heat recovery systems, energy supply methods and process operating conditions. It is also known as process integration, heat integration, energy integration or pinch technology [Monard, 2006].

The process data is represented as a set of energy flows, or streams, as a function of heat load (kW) against temperature (deg C). These data are combined for all the streams in the plant to give *composite curves*, one for all *hot streams* (releasing heat) and one for all *cold streams* (requiring heat). The point of closest approach between the hot and cold composite curves is the pinch temperature (pinch point or just pinch), and is where design is most constrained. Hence, by finding this point and starting design there, the energy targets can be achieved using heat pumps to recover heat between hot and cold streams. In practice, during the pinch analysis, often cross-pinch exchanges of heat are found between a stream with its temperature above the pinch and one below the pinch. Removal of those exchanges by alternative matching makes the process reach its energy target.

4.2 EINSTEIN expert system

EINSTEIN is an **E**xpert system for an **In**telligent **S**upply of **T**hermal **E**nergy in **IN**dustry [Heigl, 2014].

For optimising thermal energy supply in industry, a holistic integral approach is required that includes possibilities of demand reduction by heat recovery and process integration, and by an intelligent combination of efficient heat and cold supply technologies.

EINSTEIN is a tool-kit for fast and high quality thermal energy audits in industry, composed by an audit guide describing the methodology and by a software tool that guides the auditor through all the audit steps.

The main features of EINSTEIN are:

1. the data processing is based on standardized models for industrial processes and industrial heat supply systems;
2. Special tools allow for fast consistency checking and estimation of missing data, so that already with very few data some first predictions can be made;
3. Semi-automation: the software tool gives support to decision making for the generation of alternative heat and & cold supply proposals, carries out automatically all the necessary calculations, including dynamic simulation of the heat supply system, and creates a standard audit report
4. A basic questionnaire helps for systematic collection of the necessary information with the possibility to acquire data by distance.

The software tool includes modules for benchmarking, automatic design of heat exchanger networks, and design assistants for the heat and cold supply system.

It is a methodology that works out energy efficient solution for your production process based on renewable energy sources, e.g. heat pumps. This will lead to a significant reduction of your operating cost. The benefits of Einstein are:

- Increase in know-how for local auditors
- Reduction of energy costs and CO_2 emissions
- Improved competitiveness and saving for your company by a reduction of operating costs
- Road map for realisation of energy concepts with an economic consideration.

The present status of EINSTEIN does not include heat pumps for heat recovery and process integration. However, a new project – EINSTEIN III is presently in the stage of approval as part of the European Commission research programme EE-16-2014 "Organisational innovation to increase energy efficiency in industry", which include industrial heat pumps.

5 Research and development

Appropriate heat pump technology is important for reducing CO_2 emissions and primary energy consumption as well as increasing amount of renewable energy usage in industrial processes. The expansion of industrial applications is also important for enhancing these effects further more. In particular, development and dissemination of high-temperature heat pumps for hot water supply, heating of circulating hot water, and generation of hot air and steam are necessary. Specific problem areas are

- lack of refrigerants in the interesting temperature range
- lack of experimental and demonstration plants

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