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

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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.

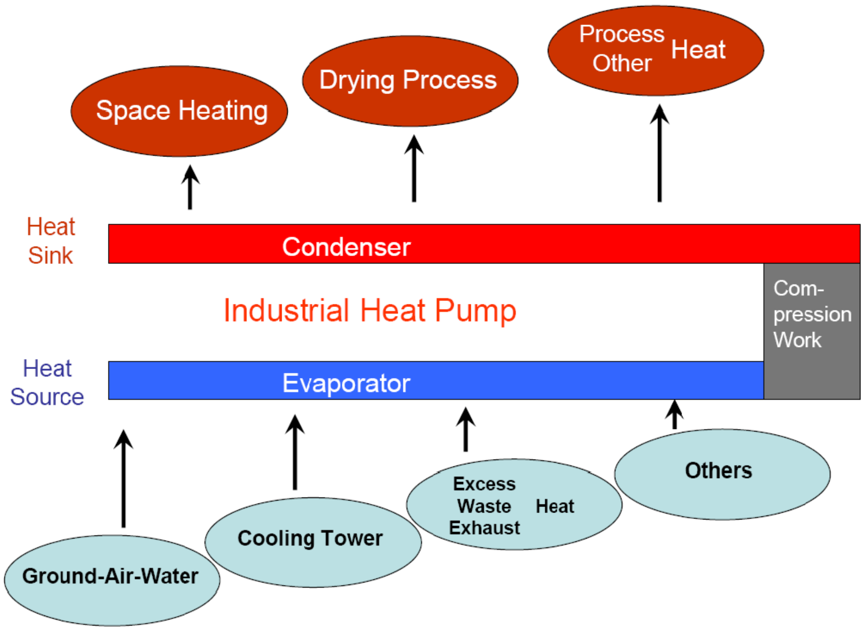

Figure 1-1: Heat sources and heat sinks in industrial heat pumps

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.

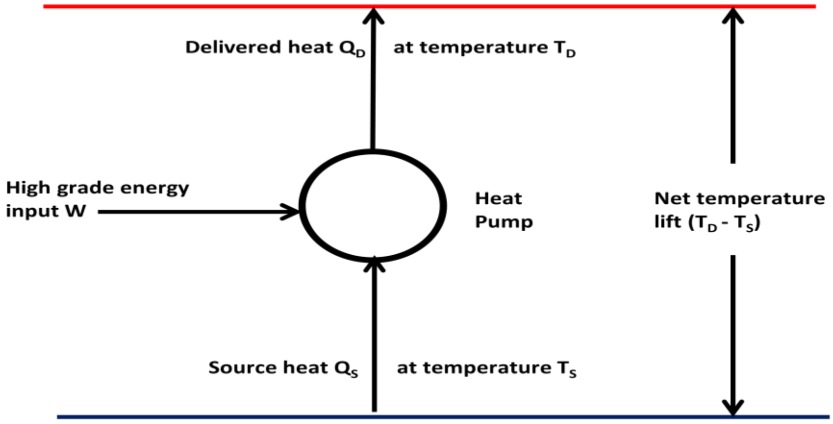

Figure 2-1: Heat pump principle

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.

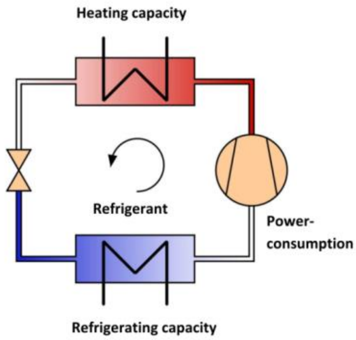

Figure 3-1: Closed compression cycle

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.

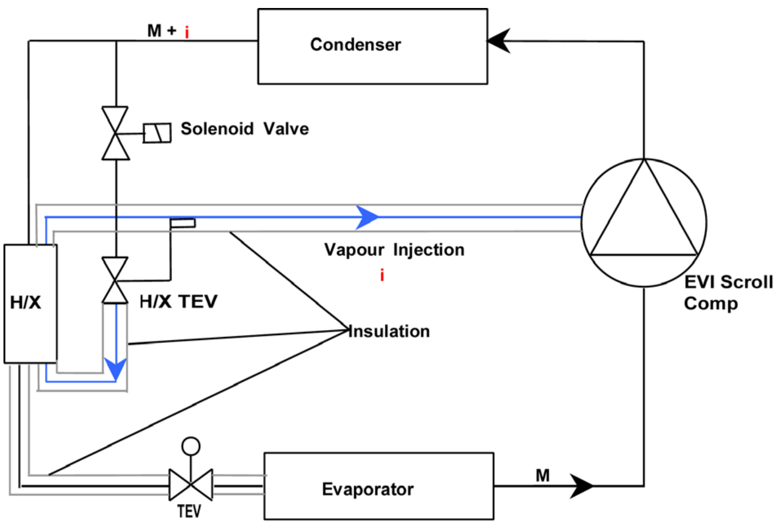

Figure 3-2: Vapour injection

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.

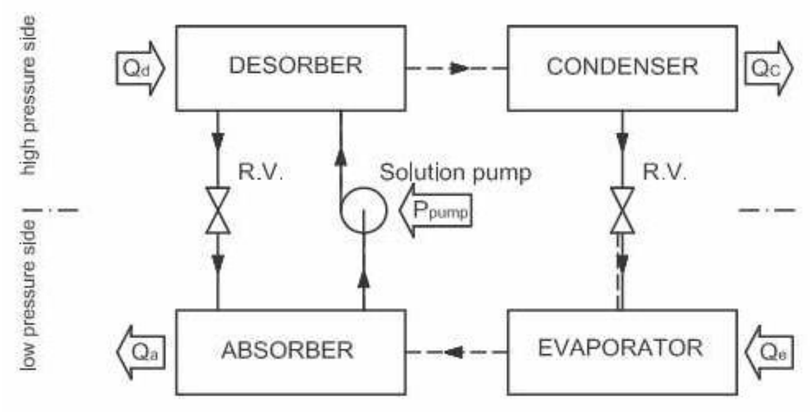

Figure 3-3: Absorption

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.

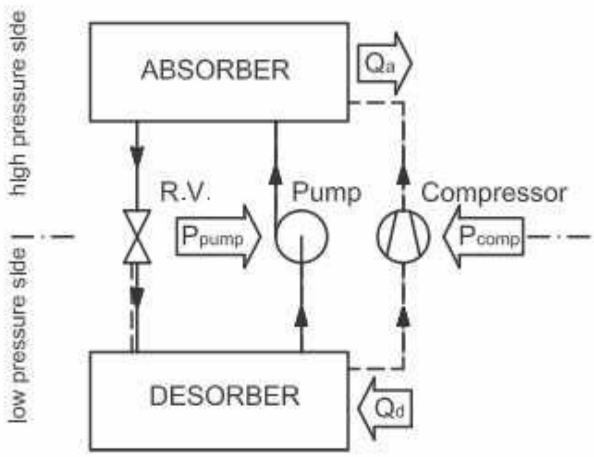

Figure 3-4: Absorption – compression hybrid

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

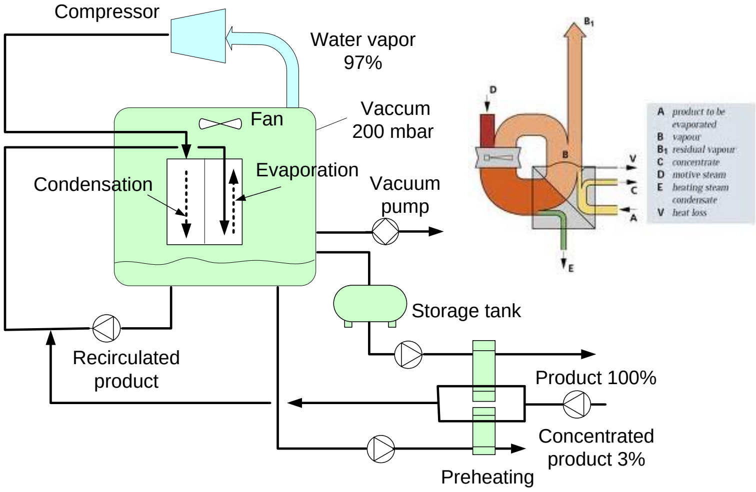

Figure 3-5: Mechanical vapor recompression [Bédard, 2002]

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.

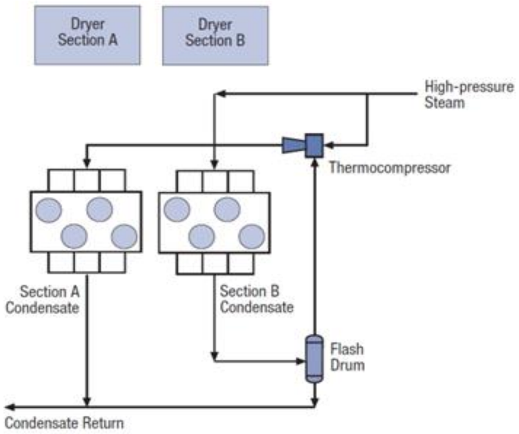

Figure 3-6: Thermal vapor recompression, Example from Japan

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.

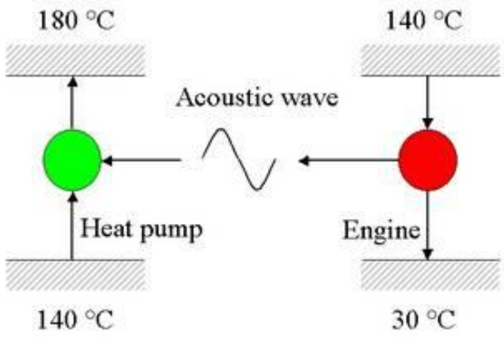

Figure 3-7: Thermo acoustic heat pump

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 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.

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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