Preliminary cost-benefit analysis for the heat pump application in industry

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Abstract— **Industry processes are characterized by large amounts of energy losses dissipated as waste heat to the ambient. In industry sectors analyzed in the US, China and EU28 low-temperature waste heat below 230ºC makes up from 33% up to 60% of waste heat. The recovery of low-temperature waste heat is usually complex, affected by the user demand, mismatches between the waste heat source and the user demand, limited space for heat recovery facilities, the heat-power conversion is not efficient for low-temperature waste heat, payback period, etc. To address these in practice frequently met issues, this paper first briefly summarizes options on the low-temperature waste heat recovery. Then, user-friendly optimization methodology integrating the heat exchange, energy conversion and heat storage is presented.**

Keywords- waste heat recovery, cooling system, heat pump

I. INTRODUCTION

The global economy growth in past few decades has come mainly from the industry and at the expense of the environment while raising primary energy consumption and CO_2 emissions. Industry processes are characterized by large amounts of energy losses dissipated as waste heat to the ambient. That waste heat manifests in different forms and at different temperatures. Waste heat recovery is the process of capturing heat from these processes to be used later directly, upgrading it to a more useful temperature, and/or converting it to electrical power or cooling. Thus, recovering waste heat can provide extra power, heat or cooling but this opportunity at the same time is a great challenge. The energy generated from heat recovery, if it not required by the process or industrial site then must be exported to neighboring facilities or electrical and/or heat distribution networks.

In the EU28, it is estimated that 70% of total energy use in the industrial sector is used in thermal processes (furnaces, reactors, boilers and dryers) and up to a third of this energy is wasted through losses. Furthermore, most of the energy sources in the industry are fossil fuels. A significant portion of this heat can be recovered and utilized to contribute to energy efficiency and greenhouse gas emission reduction [1]. In recent analysis considering waste heat and Carnot's potential estimations (Carnot's potential provides a more precise indication on whether waste heat could still perform technical work or, better, be used for heat transfer) it was shown that there is a rather significant potential accounting 370 TWh (waste heat) or 174 TWh (Carnot's) per year in the European industry [2].

The waste heat is generally classified into high-temperature (>650°C), medium-temperature (230–650°C), and low-temperature (< 230°C) waste heat [3].

The recovery techniques for high- and medium-temperature waste heat are well developed and analyzed [4], [5], [6]. Compared with low-temperature waste heat, high-temperature waste heat is more accessible to be recovered due to its high energy level and could also be used for power generation with relatively mature technologies such as a steam turbine or organic Rankine cycle. For the same reason, the application of low-temperature waste heat recovery is limited by its temperature level: suitable user demand is not always available, and the heat-power conversion is not efficient for low-temperature waste heat. All these issues lead to difficulties and challenges in effectively achieving low-temperature waste heat recovery. But according to (Z.Y. Xu, 2019) [7] in industry sectors analyzed in the US, low-temperature waste heat below 230ºC makes up ~60% of the total waste heat; in China ratio of waste heat below 150ºC is in the range from 44% to 66% (depending on the industrial sector) and in the 28 countries in European Union, one-third of the waste heat has temperature level below 200ºC.

The recovery of low-temperature waste heat is usually complex, affected by the user demand, limited space for heat recovery facilities, payback period, etc. Besides, there are many choices for waste heat recovery and conversion.

Here are listed three most common barriers that prevent wide applications of low-temperature waste heat recovery:

- There is a lack of methodology for the heat exchange network optimization when the heat-work conversion is concerned.
- Distributed waste heat recovery increases the installation space requirement, initial investment and operation costs.
- Mismatches between the waste heat source and the user demand on time, space and energy grade limit the potential of waste heat recovery [7].

To address these in practice frequently met issues, this paper first briefly summarizes options on the low-temperature waste heat recovery. Then, user-friendly optimization methodology integrating the heat exchange, energy conversion and heat storage is presented.

II. CURRENT OPTIONS – CONVENTIONAL METHODS

Options for waste heat recovery can be classified into direct use (using passive technologies) and heat conversion (using active technologies) – Figure 1.

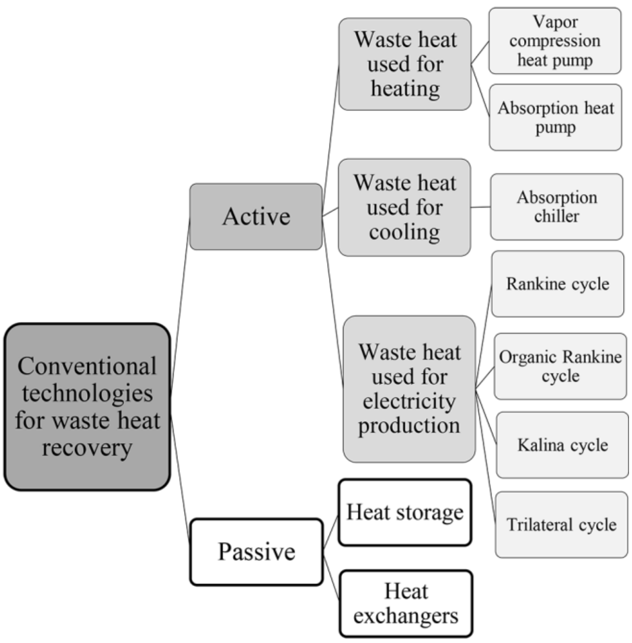

Figure 1. Classification of conventional technologies for waste heat recovery [8]

Direct uses of the waste heat include radiation/convection recuperator, passive air preheater, waste heat boiler, economizer, plate heat exchanger, etc. [9]. Heat conversion systems convert the waste heat into heat with different temperatures, cooling or power output. This offer more options for the users, which is important for waste heat recovery.

The benefits of using waste heat recovery current options are multiple:

- fuel savings,
- generation of electricity and mechanical work,
- reduced cooling needs,
- reduced upfront investment in case of a new facility,
- increased production and
- reduced greenhouse gas emissions [1].

The integration of industrial low-temperature waste heat into the energy supply is of great importance. However, measures can only be taken and evaluated after a detailed, specific and case-by-case analysis and study of production companies and processes. Our approach was to make a simple methodology that could be used for preliminary cost-benefit analysis based on data collected from power monitoring. With this methodology, we aimed to better couple the waste heat source and user demand time-scale using a heat pump and heat storage, promoting simple and user-friendly optimization.

III. USER-FRIENDLY OPTIMIZATION METHODOLOGY WITH PRELIMINARY COST-BENEFIT ANALYSIS

The presented methodology is based on waste heat recovery from cooling systems using vapor compression heat pump and is already implemented in different companies with different operation processes (induction heating machines, printing machines, etc.). For easier presentation here is presented a use case with induction machines.

A. Method of Cooling

There are many possibilities for cooling to be provided for induction machines. Smaller induction machines commonly use water-to-water plate heat exchangers and point-of-service air-cooled chillers. Larger induction installations include open evaporative tower, an air-cooled heat exchanger (dry cooler), closed-circuit cooling tower and hybrid cooling systems using closed-tower with free-cooler or a combination of chiller with free-cooler for reducing energy consumption and minimizing water usage.

An open evaporative-tower water system is commonly used for cooling multiple induction machines in the 100 – 1,000 kW range (or higher) and can produce 30°C water in every climate [10]. As shown in figure 2, water is pumped from the tower water reservoir to the plant and the cooling tower. The cooling tower uses a fan to draw air through the tower where it comes in direct contact with the water that cascades down through the tower. Heat is rejected to the air by evaporation of a small amount of water (1%) in the cooling tower as it comes in contact with the air.

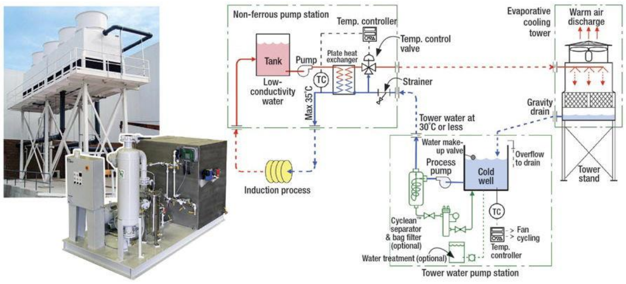

Figure 2. An open evaporative-tower water system [10]

In the use case – a plant with three operating sections (figure 3), for cooling induction machines, furnaces, presses, and other equipment are used above mentioned open evaporative-tower water system with plate heat exchanger.

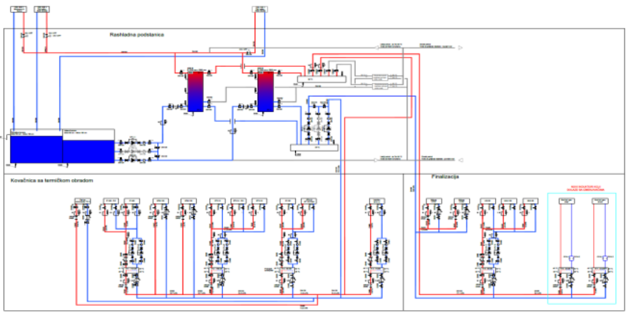

Figure 3. Layout of the plant

The existing system for cooling consists of three independent cooling systems each connected to its own cooling tower, with independent circulation pumps and pipelines. Cold-water is supplied to consumers at a maximum temperature of 30ºC. The temperature of the output water from the consumers, which is sent to the towers, is in the range of 35-45ºC. In periods of high outdoor temperatures, when it is not possible to provide 30ºC cooling water with cooling towers, there is a downtime in the operation of production plants.

According to measurements, the maximum electric load does not exceed 500 kW. Since the cooling capacity of the individual cooling tower is greater than 500 kW of cooling energy, it is concluded that with the central cooling system and the current intensity of work, one tower in operation will be enough for cooling needs of all consumers. Currently, due to separate cooling systems, all three towers are in operation, since at least one consumer in each plant section is in operation. The disadvantage of the existing decentralized cooling system is also in the unreliability of the system, considering that due to the failure or maintenance of one of the cooling towers, the entire plant section connected to that tower stops working.

B. Proposed solution

To improve the efficiency and reliability of the cooling system, one central cooling system has been designed, to which all three existing cooling towers are connected.

The reconstruction envisaged that the cooling towers will remain in the places where they are currently located, and the cold water from the cooling towers will be led to the central open reception tank (3.5 m^3) located in the cooling facility. For the accumulation of cooling water is designed to install two heat storages (buffer tanks), with a volume of 4.0 m^3 each. The required number of cooling towers for operation is determined based on temperature probes installed in a buffer tanks. Buffer tanks will be connected with high-temperature heat pump, which would provide reliable cooling of equipment even at high outdoor temperatures in the summer and the use/recovery of waste heat for the heating production plant in the winter.

Cold water circulating through the induction machine cooling system is exposed to electromagnetic fields and high voltage potentials, resulting in erosion and corrosion. Poor water quality can quickly lead to clogged cooling passages, causing equipment to run hot, to arc and at the end, to significant replacement costs. Therefore, it is necessary to use clean, low-conductivity water that would be regularly monitored. Since cooling with demineralized water, with a maximum conductivity of 20 µS/cm is provided for induction generators, plate heat exchangers are placed in front of the induction generators.

C. Preliminary cost-benefit analysis

A tool for preliminary cost-benefit analysis is made using Excel. The tool consists of nine Excel tabs. The role of individual tabs will be described below.

The Overview tab (figure 4) is a key summary tab thanks to which it is possible to manipulate data, read results and have an insight into all key data necessary for sizing a heat pump and assessing the potential for energy savings.

Figure 4. Excel tab 1: Overview

The heat pump capacity is calculated through two steps:

- Step 1 defines the minimum heat pump power. The minimum theoretical power of the heat pump (for a specific use case), is approx. 99 kW of heat and approx. 29 kW of power. This heat pump is not recommended, as it would require a significant investment in a high capacity buffer tank.
- Step 2 defines the practically usable, optimal heat pump power, based on the average days (Mon -

Fri) and the load during those days. According to the data, the highest heat load occurs during the average Monday at 9 o'clock (159 kW). This value does not correspond to the maximum heat load during the observed period (January - April 2019) which is about 280 kW, but this heat load can be removed by a heat pump of 159 kW (adopted power of 200 kW) with a buffer tank of appropriate dimensions.

Follow-up procedure, (step 3) defines the planned operating time of the heat pump during the working week (Mon-Fri) which influence the equipment payback period. In this specific use case, it would result in 6083 € per year savings of natural gas for heating. More hours of work will result in greater energy savings and vice versa.

The system with integrated heat pump is designed to operate in one of five operating modes.

- All-day operation of the heat pump on days during which both the minimum and maximum daily temperature is lower than 12˚C (the value can be changed). There are 115 such days in a year.
- Heat pump operation combined with cooling tower operation on days during which the minimum daily temperature is lower than 12˚C, and the maximum temperature is lower than 25˚C (values can be changed). There are 40.5 such days in a year.
- All-day operation of the cooling tower on days during which the maximum daily temperature goes from 12˚C, and up to 25˚C (values can be changed). There are 171 such days in a year.
- Heat pump operation combined with cooling tower operation on days during which the minimum daily temperature is higher than 12˚C and lower than 20˚C, and the maximum daily temperature is lower than 30˚C (values can be changed). There are 31 such days in a year.
- All-day operation of the heat pump on days during which the minimum daily temperature is higher than 20˚C and the maximum daily temperature is higher than 30˚C (values can be changed). There are 7.5 such days in a year.

Three scenarios were considered:

- Scenario 1: implementation of high capacity buffer tanks and use of existing cooling towers;
- Scenario 2: using a heat pump and existing cooling towers for the cooling system and space heating;
- Scenario 3: using a chiller and existing cooling towers for the cooling system.

Labor costs during the considered scenarios, as well as possible energy savings can be seen at the bottom of the table.

Excel tabs from two to nine are supporting and calculating tabs for the Overview tab (tab 1). The Diagrams tab (figure 5) gives the possibility of visual insights into the thermal load of induction machines and furnaces, i.e. the amount of heat that needs to be removed to allow continuous operation of the equipment. The diagrams cover different periods, from four-month, through weekly to daily.

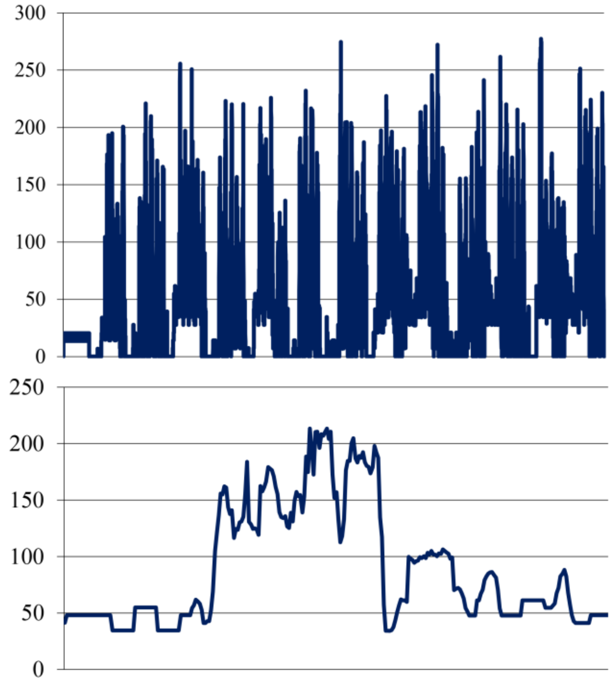

Figure 5. Quarterly (above) and 24h load (bellow) of induction heaters (kW) in use case

All other tabs (from three to nine, respectively) are used for:

3) Systematization of data obtained by measuring electricity load on individual inductors, the estimated thermal load as well as the amount of thermal energy generated per day. The data from this tab is used for some of the pivot tables.

4) Identical to Tab 3, with the difference that holidays are excluded (the first 6 days of 2019) so as not to underestimate the estimated power of the heat pump and other devices.

5) The minimum and maximum temperatures for location (Gornji Milanovac for the use case) according to NASA data (https://power.larc.nasa.gov/data-access-viewer/) for two years 1.1.2017. - 31.12.2018.

6) Pivot table defining the time of switching on (starting) the heat pump for the period Monday - Friday (working days) of the reference period.

7) Pivot table defining the time of switching off (stopping) the heat pump for the period Monday - Friday (working days) of the reference period.

8) Pivot table used to dimension the heat pump. Sizing is done based on the average heat output available for the selected period (Step 2 (red fields) of the Overview tab).

9) Pivot table, which defines the minimum power of the heat pump. A pump whose power would be less than the minimum power would not be able to cope with the heat load regardless of the size of the buffer tank. The purpose of the tab is to avoid logical errors that can occur.

IV. CONCLUSION

The initial intention of the approach presented here is to help companies dimension solutions that would save energy. Such assistance, according to the author's experience, is more than necessary for several reasons. The main reason is that the approach to proper sizing of solutions for waste heat recovery, as a rule, remains unclear or in a kind of grey zone. Although the decision-makers are often familiar with possible solutions and ways in which they could benefit from the implementation it ends in precautionary oversizing or even leaves space for equipment suppliers to deliver the equipment with a capacity larger than necessary.

When designing this solution, special attention was paid to the user-friendliness and transparency of the solution, in order to enable decision-makers and implementing engineers to approach the introduction of changes in the plant with full understanding and to empower them during negotiations in the procurement of equipment.

Opportunities for further improvement of the approach proposed here are significant, in the first place they relate to finding the optimal solution and automation of the procedure, which would minimize the human factor and errors that could affect the decision-making process.

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