CHEMICAL ENGINEERING TRANSACTIONS

VOL. 70, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870132

Dimensioning of Heat Pump Systems Based on Pinch Analysis and Energy Monitoring Data

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In this paper, typical process chains of metal processing/gear manufacturing are examined according to the pinch method with regard to their potential for heat recovery and their suitability for heat pump applications. The focus is on machine tools and parts washing machines as fluctuating heat sources and sinks. Heat sources at a low temperature level, such as the cooling of machine tools, are becoming increasingly important in contrast to conventional fossil waste heat sources due to the electrification of energy and production systems. Based on energy monitoring data from a real production system, this paper uses a simple example production line to illustrate the extent to which both the interdependencies in a material flow and a varying system size increase the energy efficiency of the overall system and how they influence the dimensioning of heat-pump-storage-solutions. Finally, the inclusion of statistical fluctuations and their significance for thermal crosslinking of production machines is discussed.

1. Introduction

The potential of waste heat utilisation in the industry is huge. The biggest share of this potential is made up by the metalworking industry (Brueckner et al., 2014). For example, Kurle et al. (2016) analysed heat sources and sinks for a gear production use case. Beside the listed hardening processes and the turning machine, classical sources of waste heat in the gear production are central utilities like compressed-air-systems, compression chillers and fossil-fired power plants. Having such a vast number of low-cost sources, relatively expensive technologies like heat pumps are usually not economic. Following the principles of process integration (Klemeš, 2013) the primary aim is to get the most out of available waste heat via optimised heat exchanger networks.

Due to the general energy system transformation, increasing electrification in all sectors is required (Hoffmann et al., 2015). In order to achieve global climate protection targets, conventional waste heat sources should be replaced in the long term. As a consequence of the German tax rebate for heat from electric current (StromStG §9a) this forced development can be already observed: Instead of natural gas-fired hardening ovens, electrically operated vacuum hardening systems are installed, compressed air-powered drives are replaced by electric drives and fossil power plants make way for e.g. wind power and photovoltaics. If today’s abundant waste heat sources are no longer available in the future with increasing electrification, heat sources such as spindle cooling in tooling machines at a low temperature level (25 - 30°C) will become increasingly attractive for the heat supply of other processes. Since the heat requirement in mechanical manufacturing systems is generally higher than 30°C, the use of heat pumps is therefore recommended. Heat pumps can thus be a central component for an enhanced sectoral coupling of electricity and heat (Beck and Sielaff, 2013). Philipp et al. (2018) reveal the ecological advantages of heat pumps with a certain proportion of renewables in the energy mix. In the field of machining Junge et al. (2017a) optimised the thermal crosslinking and temporal decoupling of one cutting machine’s heat source and one aqueous parts cleaning machine’s heat demand by one heat-pump/storage solutions (HPS). They demonstrated that for their specifically dimensioned HPS an increase of energy efficiency of 16 % is feasible.

The novelty of this study as an extension of Junge et al. (2017a) is the dimensioning of an HPS considering a material flow system including several manufacturing machines like cutting, grinding, milling and honing processes (heat sources) as well as several cleaning machines (heat sinks), as part of the production line. Moreover, this study addresses the fact that manufacturing machines in modern, energy efficient production

Please cite this article as: Seevers J.-P., Schlosser F., Peesel R.H., Hesselbach J., 2018, Dimensioning of heat pump systems based on pinch analysis and energy monitoring data , Chemical Engineering Transactions, 70, 787-792 DOI:10.3303/CET1870132

lines with central standby control (Goy, 2016) can pose a highly volatile energy demand over time depending on the material throughput (Abele et al., 2015). This is fundamental to the overall system energy efficiency as heat pumps - integrated correctly according to the rules of the Pinch method - need a constant capacity utilisation. Smoothing this volatility can be ensured by correct storage dimensioning. Furthermore, the correct integration through the pinch point can tap large efficiency potentials, a false one can even increase the energy demand (Kemp, 2007).

Section 2 outlines the technical background regarding the energy demand of parts cleaning machines as typical heat sinks as well as typical machine tools and their components with the focus on cooling processes. Based on this, the research needs are formulated. The methodological approach of this paper is described in section 3 followed by a case study analysing energy monitoring data from a production system in operation in section 4. Finally, section 5 concludes this paper.

2. Heat sources and sinks in parts production systems

Practical experience shows that in typical metal-working production lines approx. 2/3 of the total energy costs are allocated to milling, turning, grinding, honing and parts cleaning processes. A large part of the energy input is used for process conditioning (cooling, lubrication) with the main drives (main spindle, feed axes) only accounting for a proportion comparable to that of the active cooling units (Denkena et al., 2011). Accordingly, the foreseeable savings potential is also largely determined by measures to improve the auxiliary drives. Auxiliary components are typically cooling lubricant system components like pumps and filter elements, hydraulics, compressed air unit, chiller (pumps, compressor, fans) and a certain base load (Abele et al., 2015; Junge et al., 2017a).

For example, energy savings of 50 % can be achieved for the cooling lubricant systems of machine tools with a demand-oriented lubricant supply (Rahäuser et al., 2012). With cooling units, it is also possible to save more than 60 % of electrical energy with a demand-based control system and the use of a buffer heat storage (Augenstein et al., 2012). Figure 1 shows the electrical power demand of a cooling unit of a cutting machine being independent of the thermal load of the system, although the thermal load is higher in machining mode than in operational mode due to the power peaks of the spindle drives. This is the opposite of an energy efficient system with proper demand-driven control. Following the principles of the onion layer model (Kemp, 2007) the first step to enhance the rate of energy efficiency is the correct sizing and demand-oriented control of all machine components which can save significant amounts of electrical energy (e.g. Li et al., 2011). Figure 1 illustrates the effect of a standby-control where the electrical as well as the thermal energy demand can be decreased to 0 kW in stand-by mode.

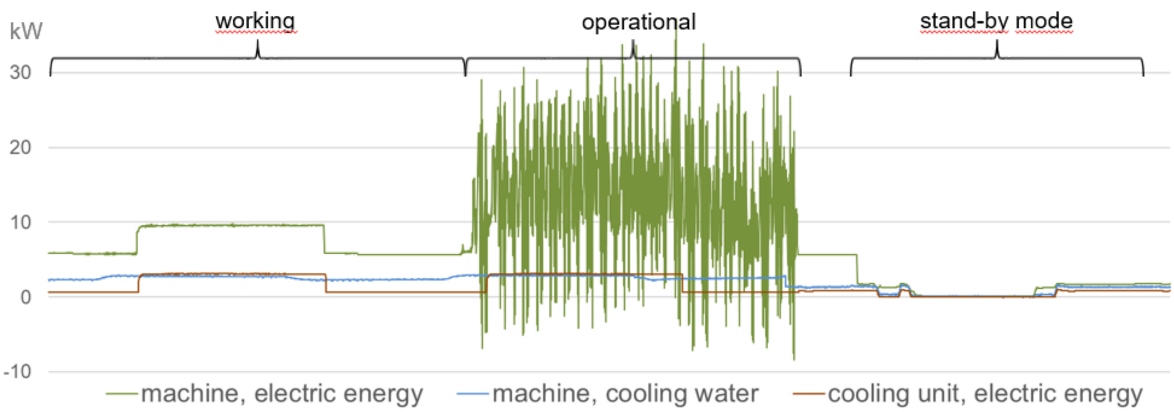

Figure 1: Machine tool during working and operational mode with electric and thermal power demands

Parts cleaning machines also have a fluctuating thermal load which depends on the current capacity utilisation. The more parts are handled, the higher the thermal energy demand for the same volume flow rate the washing medium, which in practice is usually water including chemical additives of washing water. Parts cleaning systems are available in a wide variety of designs (Junge et al., 2017b). A basic distinction is made between spray and immersion cleaning. Both types of processes have a relatively high heat demand (temperature range: 50°C – 60°C) of washing water (see Figure 2) compared to the cooling power demand of the machine tool shown in Figure 1.

Figure 2 shows a typical continuous flow cleaning system with cooling water cooled steam condenser. In the system concerned, the thermal power demand in average is not considerably higher than the electrical power demand required for the remaining components such as feed pumps and fans. This ratio differs greatly from machine to machine and depends on numerous factors such as component size, washing water tank, outside temperatures, etc. Figure 2 also reveals that the thermal demand varies depending on the capacity utilisation of the machine, while the electrical demand does less. With an intelligent standby control, both the electrical and thermal power demand should be reduced to 0 kW if the machine waits for parts more than a certain minimum period of time.

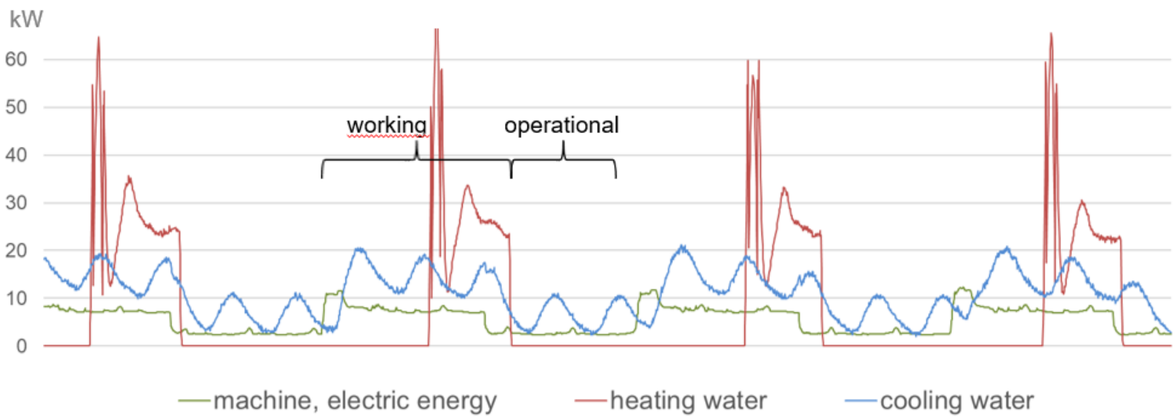

Figure 2: Parts cleaning machine during working and operational mode with electric and thermal power demands

Assuming fluctuating heat demands of the parts cleaning systems and fluctuating cooling needs, which will occur more and more frequently in a future demand-controlled production with automated optimal standby operation (Goy, 2016), an optimum HPS design depends on the system size respectively on the number of heat sources and heat sinks. The research of Stoltze et al. (1995) has shown that a theoretically large number of heat storage tanks (double the number of process streams) can be reduced to just a few tanks. In the case of a parts production system with a varying number of heat sources (machine tools) and sinks (cleaning machines) the optimal HPS dimensioning for a given parts production system size has to be made by assuming a certain workload. Furthermore, influencing environmental factors, material flow interruptions and optimised material flow controls (standby control) must be considered.

3. Methodological approach

This study introduces a methodology to rapidly determine the optimum HPS adapted to certain scenarios with the following steps:

1. Analysis of heat and cooling demand measurement data based on scenario generation
2. HPS-dimensioning by using Pinch-Analysis

3.1 Scenario generation

First, a certain material flow (sub-)system with a certain number of machines is selected. Measured thermal energy flows for the different operating states “working” and “operational” are given with a statistically determined variation range, which is determined both by Gaussian measurement error propagation law and by random process fluctuations. Subsequently, for certain scenarios, e.g. full workload vs. partial workload or standard material flow control vs. optimized stand-by control, the accumulated cooling demand and heat demand power curves are determined. The cumulative sum curve for the cooling demand is the sum of cooling water and lubricant cooling demand of all machines of the analysed production line. Based on these sum curves in combination with the pinch analysis, the HPS system can be sized. Figure 3 shows scenarios for the utilization of the production line. In the partial load 50 % scenario, the machines gradually run empty on parts to be machined and change from working to operational mode.

Figure 3 also shows the relevance of varying heat and cooling demands of machine tools and washing machines: Machine tool 1, for example, has the same cooling demand for cooling water in operational and working mode and a similarly high demand for cooling lubricant in both operating states. Whereas machine tool 2 has a significantly lower overall average cooling power demand than machine tool 1 and a higher power difference between the operating states. The cleaning machines are also very different due to different storage dimensioning and flow control. Cleaning machine 1 can significantly reduce its heat demand during operational state, while its cooling demand decreases relatively little and is at a significantly higher level than the cooling demand of cleaning machine 2.

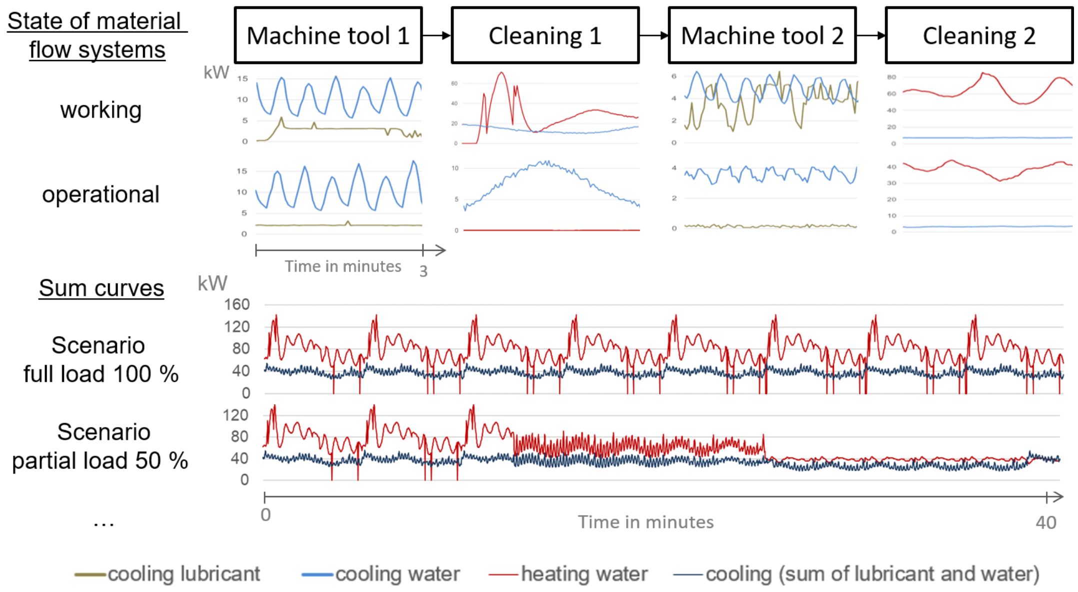

Figure 3: Linking material flow and thermal energy flow

3.2 Heat Pump Integration based on Pinch-Analysis principles

The pinch analysis is a tool with which all occurring energy flows are recorded and displayed graphically, sort by temperature and load. This graph (called Composite Curves) shows the potential for heat recovery and proper integration of HPS (Kemp 2007). Figure 4 represents the Grand Composite Curve (GCC) of the system in which the heat recovery potentials are already unlocked and only the remaining heating and cooling demand at the associated temperature level is quantified. The Pinch temperature is the heating-cooling-limit of the thermodynamic system. The Pinch divides it into a zone with pure heat demand (above) and one with pure cooling demand (below). Consequently, the Pinch has a special significance for the integration of the heat pump.

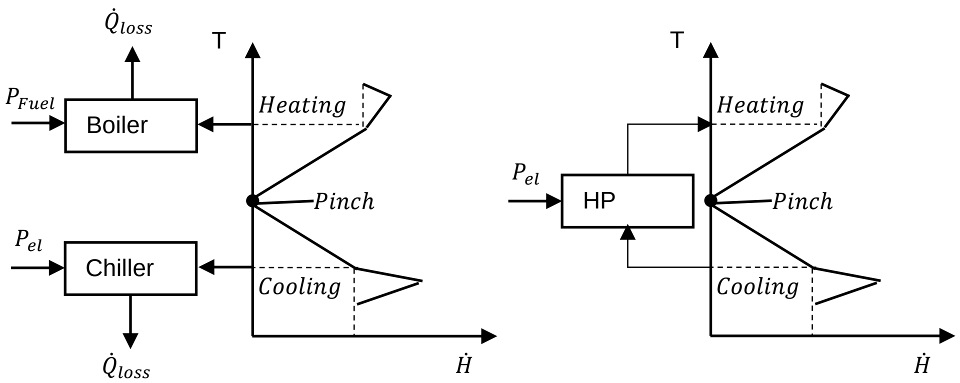

Figure 4: Integration of a conventional supply system by contrast with a heat pump through the Pinch based on the GCC.

While heating and cooling by conventional supply systems, such like boiler or chiller, the heat pump efficiently provides both types of useful energy simultaneously. In addition to the reduced final energy input, waste heat losses to the environment (recooling and exhaust gas) are avoided. The GCC specifies the correct integration of a heat pump through the pinch, as illustrated in Figure 4. A pure integration below the pinch even increases the cooling effort, a heat pump above the pinch works as an inefficient electric heating element.

3.3 Storage dimensioning

The coupling of cooling and heating requires the use of storages to balance fluctuating cooling and heat demands. Depending on the storage capacity, determined by the available storage temperature difference ΔT, the uninterruptible period Δt and the load demand $\dot{Q}$ to be smoothed, the storage volume V is as follows:

$$V = \frac{\dot{Q} \cdot \Delta t}{1{,}16 \frac{kWh}{m^3 \cdot K} \cdot \Delta T} \quad (1)$$

4. Results of case study

The analysis of the real sensor data of approx. 100 manufacturing machines from the production revealed very strongly fluctuating electrical and thermal energy demands even for apparently the same machine type and size. This is partly due to a lack of measurement system maintenance and a lack of automated measurement error detection (Jäger et al., 2014), and partly due to strongly fluctuating process variations, which are dependent on a large number of production environment factors. For further analysis the production line, shown in Figure 3, is chosen. It is supplied by hot water of 55 °C for temperature conditioning of the cleaning water and cooling water of 25 °C for cooling the machine tools.

4.1 Integration of HP according to Pinch-Analysis

The Pinch temperature of this case study is 55 °C. For a global minimum temperature difference ΔT_{min} of 10 K, the target temperature of the heat pump is 65 °C and 15 °C on the cooling side. Thus, the heat pump must provide a temperature difference of 50 K, what is at the upper limit for single-stage heat pumps. The integration of the heat pump consequently takes place according to the pinch analysis principles (3.2). To balance load and demand, the storage allows a temperature difference of $\Delta T = 5\ K$.

4.2 Storage dimensioning

In the 50 % workload scenario shown in Figure 3, the 40-minute performance curve can be roughly divided into three sub-areas, each with a time span of approx. 12-14 minutes. In the first area, the cumulative heat demand of the line is approx. 75 - 80 kW on average, the cooling demand is approx. 40 kW on average. In the second range, the ratio is around 60 to 35 and in the last range, in which all machines have switched to the operational mode, the heat demand has dropped to a relatively constant 40 kW and the cooling demand fluctuates with 5 kW by an average output of 25 kW. The COP of the selected high-temperature heat pump with EVI (Enhanced Vapour Injection) refrigerant circuit which reaches a flow temperature of up to 72 °C is around 2.5 in the considered temperature range (Junge et al., 2017a).

Partial load is the most common case that occurs on the line in question. Full utilization due to limited machine availability as well as zero utilization only occur for short periods of 30-60 minutes. 35 kW of cooling capacity (cold-guided operation) would generate around 58 kW of heat. The remaining heat demand in the case of full utilisation would have to be covered by an electric heating rod, for example.

If the load drops slightly within 20 minutes as in the example partial-load-scenario and the load then drops to zero, the heat as well as the cold storage should be able to buffer this production break as long as possible:

Difference of heat demand and heat supply at zero load: 40 kW – 58 kW = - 18 kW

Difference of cooling demand and cooling supply at zero load: 25 kW – 35 kW = - 10 kW

If now a complete production interruption of the line is to be buffered for one hour, the heat storage according to Formula 1 would have to be about 3.1 m³ and the cold storage about 1.7 m³.

4.3 Scenario analysis

Assuming a standby control would shut down the two parts cleaning machines into standby mode, in which both cooling, and heating demands would fall to 0 kW. This would result in a cooling demand of approx. 22 kW due to the two machine tools. The heat storage, dimensioned in section 4.2, could bridge such an interruption for a maximum of 20 minutes.

5. Conclusions and outlook

The exemplary case study of a very small production line showed that heating and cooling demands can be linked quite well with a certain HPS dimensioning. However, the higher the process fluctuations and measurement uncertainties, the larger the storage must be dimensioned if the process reliability or material flow would otherwise be affected. A production line as small as the one under investigation in this study is all the more sensitive to process fluctuations or any change in environmental conditions. Especially when heat and cooling demand can vary greatly, even with similar machine types and dimensions. The larger the material flow

or production system included in the HPS supply, the less likely it is that heating and cooling demands will occur at the same time. However, energy efficient standby control systems considered in chapter 4.3 can also cause a sudden drop in the power level of heat sources or sinks by switching off individual components of the system. In this case, too, the smaller the HPS-linked system, the stronger the effect and the bigger heat and cooling storages have to be dimensioned.
Apart from the sources of uncertainty described above, there are many others that complicate a deterministic and stable dimensioning of the HPS system. Therefore, a profound consideration of statistical influences is part of further research. Promising in this context is the combination of physical models of HPS components with a Monte-Carlo based material flow simulation.

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