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Load Optimization of Heat Exchanger Cascades

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Introduction

Central heat transfer networks (CHTN) are popular in the Central and Eastern Europe. For instance, there are more than 700 CHTNs in the Czech Republic [1]. CHTNs are used to provide the consumers with heat energy in the form of hot water or steam. The consumers use heat exchanger stations (HES) to transform this energy into hot water for heating or hot water.

There are two types of heat exchanger stations – object and district HESs. Object HES is typically equipped with one heat exchanger that provides satisfactory power for given building. District HES, on the other hand, need to cover larger power ranges. Therefore, these HESs are typically equipped with several heat exchangers working in parallel. Parallel working heat exchangers are often referred as heat exchanger cascade.

This paper focuses on the district HESs, especially on the optimization of heat exchanger cascades. The main motivation is following. Whilst in the past, there has been a significant amount of industrial research into optimization of the heat exchanger performance; to the best of our knowledge optimization of the load control of the heat exchanger cascades has not been thoroughly studied. Hence, the load control of heat exchanger cascades is still sub-optimal. In other words, heat exchanger cascades are operated just to provide the required output. The load of individual heat exchangers is not optimized in terms of overall efficiency.

However, as will be presented here, significant efficiency increase can be achieved with a simple algorithm that optimizes the load of each heat exchanger. The basic idea uses the fact that the efficiency of each heat exchanger is not constant. In fact, it depends on its load.

Furthermore similarly to the CHTNs, there are two types of heat exchangers steam-water and water-water. This paper deals with the steam-water heat exchangers. However, the conclusions are general and directly applicable to both types of heat exchangers.

The structure of this paper is as follows. Firstly, a typical heat exchanger is presented and its efficiency is defined. Secondly, an empirical model for heat exchanger efficiency as a function of heat exchanger's load is introduced. Lastly, the load-optimization algorithm is presented and the potential energy savings are explored and quantified.

Heat exchanger

Currently, most heat exchanger stations employ helical heat exchangers or plate heat exchangers [2, 3]. For the calculation of heat exchanger efficiency, following equations (1)-(3) are needed.

The input energy is calculated as follows

$$W_1 = m_S \cdot \left[\left(h_S - h'' \right) + R + c \cdot \left(\Theta' - \Theta_K \right) \right], \quad (1)$$

where W_1 – input energy [J]; m_S – steam mass [kg]; $h_S; h''$ – input steam enthalpy; at saturation level [J kg^{-1}]; R – evaporation heat [J kg^{-1}]; c – specific heat capacity of water [J kg^{-1} K^{-1}]; $\Theta'; \Theta_K$ – evaporation temperature; temperature of condensate water [K; °C].

The output energy is given by:

$$W_2 = m_V \cdot c \cdot \left(\Theta_2 - \Theta_1 \right), \quad (2)$$

where W_2 – output energy [J]; m_V – water mass [kg]; c – specific heat capacity of water [J kg–1 K–1]; $\Theta_2; \Theta_1$ – temperature of input water;output [K; °C].

Graphically, the variables are depicted in Fig. 1. The efficiency of the heat exchanger is then obtained as the ration of input and output energy

$$\eta = \frac{W_2}{W_1}. \quad (3)$$

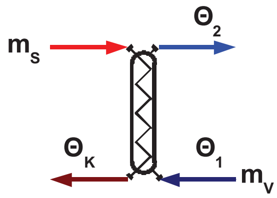

Fig. 1. Heat exchanger and measured variables

Load Dependence of Heat Exchanger's efficiency

The heat exchangers are typically controlled to keep the temperature of output water Θ_2 at a constant level [3]. Typically the value of Θ_2 is set by the maintenance managers based on their requirements. Often, the temperature Θ_2 can be reset during the year depending on the outdoor temperature. The temperature Θ_2 cannot be selected arbitrarily and is, among other factors, limited by the safety considerations.

This is illustrated by Fig. 2 which shows the real values of Θ_2 taken from the experimental heat exchanger station located at the university campus in Usti nad Labem, Czech Republic. The experimental HES consists of three indentical heat exchangers in cascade and is used to provide heat and hot water for two dormitories, a dining hall and a cafeteria. It can be observed that apart from the inevitable error of the control loop, the temperature is mostly kept close to the set target temperatures which in this case were 57°C, 70°C and 80°C.

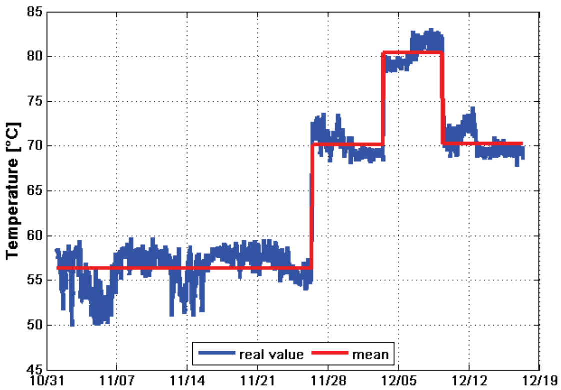

Fig. 2. Temperature of output water Θ_2 during months November and December 2010

The set temperature of output water Θ_2 was presented because it has implications for the efficiency of the heat exchanger. This is illustrated by Fig. 3, which shows the efficiency of one heat exchanger (from the experimental HES) as a function of the load of the heat exchanger. The efficiency and the input power were calculated using (1) and (3). The data used for Fig. 3 are from the same period as data from Fig. 2.

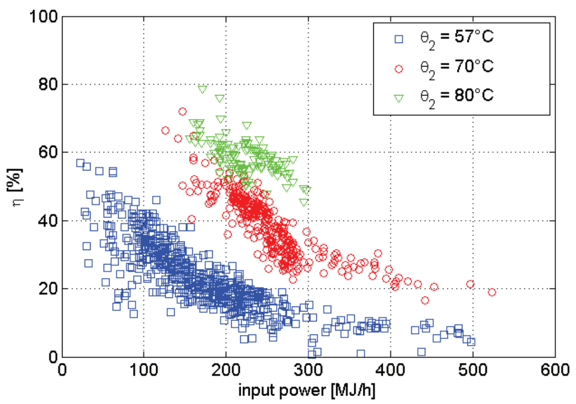

Fig. 3. Efficiency of heat exchangers with varying load

As can be observed in Fig. 3, the efficiency depends on the temperature of output water Θ_2. Whilst this is an important phenomenon that should be explored in the future research avenues, this paper focuses mainly on the dependency of the efficiency on the input power.

The data in Fig. 3 are scattered, which can be caused by several factors. Firstly, there is the impact of the output water temperature Θ_2 which varies about the mean despite the efforts of the control system. Furthermore, the measurement equipment is not designed for efficiency calculation. Hence, the measurements of input and output power are not perfectly synchronized which causes further scattering of the data points in Fig. 3 [4, 5].

Despite the scattering, a model for the dependency of the efficiency of a heat exchanger on its load can be observed and modeled using following formula

$$\eta = A \cdot e^{B \cdot W_1}, \tag{4}$$

where A, B are model coefficients specific for each heat exchanger and depending on settings such as temperature of output water Θ_2.

The model has been applied to the data from Fig. 3 and the fit is presented in Fig. 4. The model parameters are then summarized in Table I.

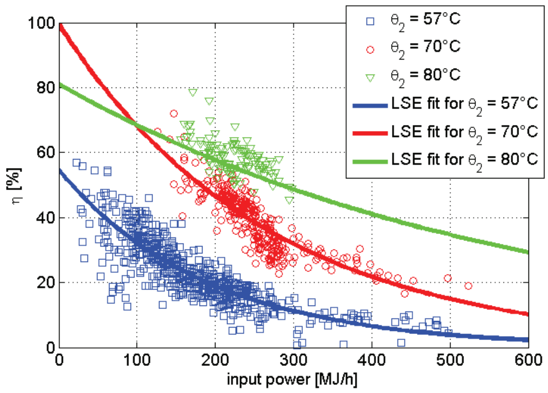

Fig. 4. Least Square Error (LSE) fit of model from (4) to experimental data

Table 1. Model parameters

Output water temperature Θ_2.	Model parameter A	Model parameter B
57°C	0.546	–0.0053
70°C	0.995	–0.0038
80°C	0.810	–0.0017

To conclude, this section has explored the efficiency of a heat exchanger. As a result, it presents an empirical model of efficiency as a function of heat exchanger's load. The conclusion is that the efficiency generally decreases with increased load. The dependency is exponential. Thus, the efficiency optimization of a heat exchanger based on better load distribution is possible and will be discussed in following section.

Load Optimization – Theory

The objective of optimization of the load distribution among heat exchangers in a cascade is to provide the required output power whilst the total efficiency is maximized. This can mathematically be expressed as follows

$$W_{2,total} = \sum_{i=1}^{N} W_{2,i} = W_{cons} \textbf{ AND } \eta_{total} = MAX, \quad (5)$$

where η_{total} is the total efficiency of the cascade; index i represents individual heat exchanger in the cascade; N stands for the total number of heat exchangers in the cascade.

The first term represents solely the fact that the total output of the heat exchanger cascade must correspond to the total consumption. This is a standard condition and heat exchanger cascades are usually controlled to satisfy this condition. However, within the constraints imposed by the limited output power of each heat exchanger ($0 \leq W_{2,i} \leq W_{2,i,MAX}$) there are infinite number of solutions. (Exception are the extremes when the output power equals the maximum power available or when it is equal to zero).

In contrast to standard algorithm, the maximization of the efficiency allows to select the single optimum setting of heat exchangers. The total efficiency of heat exchanger cascade can be expressed as follows

$$\eta_{total} = \frac{\sum_{i=1}^{N} W_{2,i}}{\sum_{i=1}^{N} W_{1,i}} = \frac{\sum_{i=1}^{N} \eta_i W_{1,i}}{\sum_{i=1}^{N} W_{1,i}} = \frac{\sum_{i=1}^{N} W_{1,i} \cdot A_i e^{B_i \cdot W_{1,i}}}{\sum_{i=1}^{N} W_{1,i}}. \quad (6)$$

Maximization of (6) can be performed using standard calculus methods

$$grad(\eta_{total}) = \vec{0} \textbf{ AND } div\, grad(\eta_{total}) < 0. \quad (7)$$

There might be more solutions to (7) representing several local maxima, the global maximum must be selected.

The individual elements j of the gradient term in (7) can be calculated as follows. The calculation of the Laplace term is, for the sake of brevity, left out as it represents only a mechanical calculation that can be conducted by the reader

$$grad(\eta_{total})_j = \frac{\left(A_j e^{B_j \cdot W_{1,j}} + W_{1,j} B_j \cdot A_j e^{B_j \cdot W_{1,j}}\right) \cdot \sum_{j=1}^{N} W_{1,i} - \sum_{i=1}^{N} W_{1,i} \cdot A_i e^{B_j \cdot W_{1,i}}}{\left(\sum_{i=1}^{N} W_{1,i}\right)^2} =$$

$$= \frac{\sum_{i=1}^{N} \left(A_j e^{B_j \cdot W_{1,j}} + W_{1,j} B_j \cdot A_j e^{B_j \cdot W_{1,j}}\right) \cdot W_{1,i} - W_{1,i} \cdot A_i e^{j \cdot W_{1,i}}}{\left(\sum_{i=1}^{N} W_{1,i}\right)^2}. \quad (8)$$

Whilst (7) looks rather complex, it must not be forgotten that in real problems, the number of heat exchangers in heat exchanger stations will be limited typically N ≤ 10 [3]. As a result, the actual number of equations that need to be solved and their complexity does not exceed reasonable level for simple signal processing by the controller.

Moreover, it must be noted that (7) does not always yield the global maximum. Theoretically, the maximum might be achieved for points representing the limit of the available interval of the input power ($0 \leq W_{1,i} \leq W_{1,i,MAX}$). This condition must be tested. Fortunately, due to the decreasing nature of heat exchanger efficiency ((4)) only the lower bound of the interval is plausible. For a non–zero output power and for at least one input power $W_{1,i} = 0$, the maximum will not always correspond to a point with gradient of (6) being a null vector, but at least one coordinate of the gradient will be zero. This further simplifies the solution and practical implementation.

Lastly, it must be mentioned that while (6) is optimized, the condition of total consumption from (5) must still hold. For the sake of clarity and simple solution, this condition can be expressed as

$$W_{cons} = \eta_{total} \sum_{i=1}^{N} W_{1,i}. \quad (9)$$

Load Optimization – Case Study

To illustrate the ability of the algorithm presented in preceding section, a case study was conducted using the experimental HES with three identical heat exchangers. The temperature of output water Θ_2 was assumed 70°C which represents the typical choice for winter period.

In Table II, the proposed algorithm of optimal load distribution is compared to the standard algorithm for typical loads. The standard load distribution algorithm currently in place distributes the load mainly to one heat exchanger. As long as the output power is below the maximum, the algorithm uses only one heat exchanger. Further heat exchangers are connected only if the output power exceeds the maximum achievable by one heat exchanger.

The optimization was performed using the algorithm presented above. Furthermore, the calculation was simplified by the fact that the HES employs three identical heat exchangers. Thus, the components of the gradient are equal and only 1/3 of the equations needs to be solved. The efficiency model from (4) was used with model parameters taken from Table 1.

Table 2. Standard load distribution compared to the optimized load distribution

W_{cons}	Standard method HE Loads [MJ/h]				Optimized method HE Loads [MJ/h]			
[MJ/h]	$W_{1,1}$	$W_{1,2}$	$W_{1,3}$	η_{tot}	$W_{1,1}$	$W_{1,2}$	$W_{1,3}$	η_{tot}
70	105	0	0	0.67	26	26	26	0.9
80	134	0	0	0.6	30	30	30	0.89
90	178	0	0	0.5	34	34	34	0.88
100	243	5	0	0.4	39	39	39	0.86
120	243	26	0	0.44	48	48	48	0.83

Conclusions

This paper has explored the issue of heat exchanger efficiency as a function of its load. An empirical model has been developed that well fits the behavior of the efficiency. It has been determined that the efficiency of heat exchanger decreases exponentially with its load.

This empirical model can be used to optimize load distribution among individual heat exchangers in heat exchanger cascades that are commonly used in larger district heat exchanger stations. An optimization algorithm has been developed and presented. The theoretical solution of the optimization has been discussed.

Lastly, the algorithm has been applied to an experimental heat exchanger station consisting of three identical heat exchangers. A case study calculation for typical output powers was performed and it has been shown that the efficiency can be significantly increased when the optimized load distribution algorithm is employed instead of the standard algorithm. The efficiency is approximately doubled for output power in the range 90–120 MJ/h. Such improvement represents significant saving for the facility manager.

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This paper explores the load variant efficiency of heat exchangers. An empirical model of efficiency as a function of heat exchanger load is presented. This model can be used to optimize the load distribution among heat exchangers in heat exchanger cascades. As a result, the efficiency of district heat exchanger stations can be significantly increased. The efficiency increase depends on the load but it can be approximately doubled for a significant interval of loads. Ill. 4, bibl. 5, tabl. 2 (in English; abstracts in English and Lithuanian).

J. Šipal. Šilumokaičio pakopų apkrovos optimizavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 3(109). – P. 93–96.

Analizuojamas šilumokaičio pakopų apkrovos optimizavimas. Sudarytas empirinis efektyvumo modelis kaip šilumokaičio apkrovos funkcija. Šis modelis gali būti naudojamas apkrovai optimaliai paskirstyti tarp šilumokaičio pakopų. Toks modelis gali būti sėkmingai pritaikytas miesto šilumos tiekimo sistemose. Tai gerokai padidintų jų efektyvumą. Efektyvumas priklauso nuo apkrovos, tačiau tam tikrais apkrovos tarpais gali būti iki dviejų kartų didesnis. Il. 4, bibl. 5, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).