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Optimization of Thermal Storage Based on Load Graph of Thermal Energy System

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Abstract

Thermal energy storage (TES) can average the loads of thermal energy systems, thus increases their energetic and exergetic efficiencies. The steam boiler plant with violently fluctuating loads is a typical example when a steam accumulator is added to it. However, the comparatively big first cost constitutes a barrier to wide use of TES. The cost will notably be reduced through minimizing the necessary thermal capacity of TES. A computer program for performing the optimization is illustrated in the paper. This program was applied to an existing boiler plant equipped with a steam accumulator. The results show that there would have been a remarkable reduction in the necessary capacity, if the capacity of this steam accumulator had been optimized. Four conclusions have been reached.

Key words: thermal energy storage, optimization, efficiency, necessary thermal capacity

1. Introduction

Thermal energy storage (TES) plays an important role in the strategy of energy conservation and economic operation of thermal energy systems. It contributes to the enhancement of energetic efficiency and the environment protection. It serves in various systems of energy utilization, such as boilers, solar heat supply systems, solar power plants, HVAC systems, etc. . *Figure 1* is the simplest diagram of most thermal energy systems with TES. For some cases, TES is indispensable to good performance of thermal energy systems. In a number of other cases, thermal storage improves energetic efficiencies when energy loads are low and, especially, frequently fluctuating with big amplitudes (*Figure 3(a)*). Besides, TES is also helpful in increasing exergetic efficiencies of energy systems.

However, the first cost of TES may be a rather big part of the total of an energy system. For instance, the cost of the thermal storage for certain solar systems can be about 3 % to 20% or even more of the total initial investment of the systems (Winter et al., 1991). In some applications the high rate of first cost constitutes a barrier to the wide use of TES. As an example, the cost of a steam accumulator for an industrial boiler plant can be up to 1/4 or so of total investment of the plant. This is one of the main reasons why steam accumulators have not yet become popular in many countries so far. There appears to be well worth reducing the cost of thermal storage so as to break down the barrier to its wide use, and to reduce the total costs of thermal energy systems.

A method is introduced in the paper for minimizing the required capacity (sizes) of the storage vessel in order to make the first cost minimum, while the maximum energetic and exergetic efficiencies of the system are still attainable, thus contributes to the optimization of the whole system.

2. The Contribution of TES to Exergetic Efficiency

As far as the increase of the exergetic efficiencies of energy systems is concerned, the very example is the steam accumulator added to industrial boiler plants under certain conditions.

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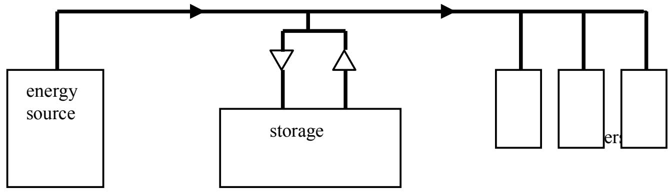

Figure 1 Energy system with energy storage

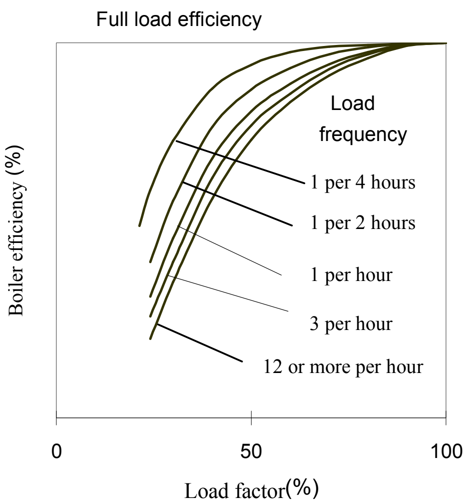

Figure 2. The effect of load fluctuation on the overall efficiency curve

As a matter of fact, the energetic efficiency of a boiler decreases rapidly with the increase in frequency of its load fluctuation (*Figure 2*) (Tanton et al., 1987). In P. R. China, e.g., the real energetic efficiencies of industrial boilers are much lower than those obtained under rated loads that are steady, the average fall accounting for 10% or so. It is because of low and highly changeable loads, which most industrial boilers in China are taking. Compared with the pressure that the user demands, the rated pressure of an industrial boiler is usually much higher. So a rise of both the energetic and exergetic efficiencies of the system could theoretically be expected if cogeneration be adopted in the system. However, it is not always the case. When using back-pressure turbine units, cogeneration would often fail in increasing either energetic or exergetic efficiencies, provided the loads of systems were at low levels and, especially, frequently and violently fluctuating. On the other hand, the increase in efficiencies due to adopting some more sophisticated types of turbine unit would not pay for the increase in the total cost (Gai and Zhang, 1994). According to the concept of cumulative exergy consumption (CExC) (Szargut, 1987; Szargut et al., 1988), this lack of economic justification implies that the savings on exergy due to increase in exergetic efficiency may not be made up for the increase in the total amount of CExC for the sophisticated systems. In other words, although cogeneration can, in general, obtain some higher exergetic efficiencies, there are often exceptions for small or medium-sized systems that operate at the fluctuating loads mentioned above. In this case, a better solution is TES, which increase exergetic efficiency, as it is going to be explained. This is why TES should be used widely. As things stand, the energetic efficiencies of the boilers can usually be raised 3% ~ 11% if steam accumulators are inserted into systems.

The well-known relationship between exergetic and energetic efficiencies of a boiler is expressed by Eq. (1) (Kotas, 1985):

$$\eta_{ex} = \eta_{en}\frac{V_f}{\varepsilon_f}\frac{(\varepsilon_{st}-\varepsilon_{fw})}{(h_{st}-h_{fw})} = \eta_{en}\frac{V_f}{\varepsilon_f}\left(1-T_0\frac{s_{st}-s_{fw}}{h_{st}-h_{fw}}\right) \quad (1)$$

Let T_m denote the mean thermodynamic temperature at constant pressure (Szargut et al., 1988).

$$T_m = \frac{h_{st}-h_{fw}}{s_{st}-s_{fw}} \quad (2)$$

Thus Eq. (1) can be transformed into following:

$$\eta_{ex} = \eta_{en}\frac{V}{\varepsilon_f}\left(1-\frac{T_0}{T_m}\right) \quad (3)$$

By differentiating Eq. (3), the increment of exergetic efficiency will be expressed through that of energetic efficiency:

$$\Delta\eta_{ex} = \frac{V_f}{\varepsilon_f}\left[\Delta\eta_{en} - T_0\Delta\left(\frac{\eta_{en}}{T_m}\right)\right] \approx \approx \frac{V_f}{\varepsilon_f}\,\xi\,\Delta\eta_{en} \quad (4)$$

Symbol ξ is adopted to simplify Eq. (4):

$$\xi = 1-\frac{T_0}{T_m}\left(1-\frac{\eta_{en}\Delta T_m}{\Delta\eta_{en}T_m}\right) \quad (5)$$

In Eq. (4), V_f / ε_f is a feature of the fuel applied to boilers, its value being around unity for most fuels (Szargut et. al., 1988). Factor ξ takes a value about 1/2 for the cases under discussion. So it is obvious from Eq. (4) that TES can increase the exergetic efficiency of boiler plant if the loads of the plant are low and frequently fluctuate with big amplitudes, and that the increase can be about half as much as the energetic efficiency in this case. In consideration of the fact that η_{ex} of boiler is usually less than half of η_{en}, the increase in η_{ex} is remarkable.

When TES is applied to some other kinds of energy systems, the principle of increasing exergetic efficiency tends, in a way, to be similar to the above, provided their energy loads are low and frequently changing (*Figure 3(a)*).

3. Minimization of the Capacity of Thermal Storage

3.1 The concept of capacity computation

Examine a system diagrammatically shown in *Figure 1*, and assume that *Figure 3(a)* shows the load curve of an operation cycle of the system. There is always the difference D(t) between mean load M over the cycle and instantaneous load l(t) of the system.

$$D(t) = M - l(t) \tag{6}$$

The integral curve — function L(t) —throughout the cycle can thus be expressed as following.

$$L(t) = \int_0^t D(t)dt \tag{7}$$

Obviously, L(t) is the thermal energy accumulated in the storage vessel from the beginning of the cycle to the moment t. Therefore, the distance C in *Figure 3(a)* is just the capacity of the storage vessel necessary to meet the requirement of normal operation of the system.

$$C = L_{max} - L_{min} \tag{8}$$

It is easy to determine the sizes of the storage vessel corresponding to the C through certain formulas applied to various applications of TES.

However, the C above obtained is usually rather big. To reduce the value of C, a well-known method is to suitably divide the cycle into several segments, and then use Eq. (7) to each segment. The resultant difference C in *Figure 3(b)* over whole cycle will then be the necessary capacity that tends to be noticeably smaller than does the original C in *Figure 3(a)*. It appears to be necessary for developing an algorithm to find out an optimized mode of dividing the cycle so as to make the C minimum, and to guarantee the highest efficiency attainable for each unit in the boiler plant that delivers thermal energy to consumers of the system.

3.2 The algorithm for the optimization of thermal storage capacity

It is obvious that there are a lot of patterns of segmentation can be made. For any segmentation, the k-th one, the load cycle is assumed being divided into N segments (*Figure 3(b)* similarly) numbered from 1 to N. τ_{i-1} and τ_i denote the moments at the beginning and the end of No. i segment respectively. Since the values of integrals of $L_k(\tau_i)$ equal zero when $t = \tau_i$ ($i = 1, \ldots, N$), it follows that Eq. (7) can be transformed into the following form:

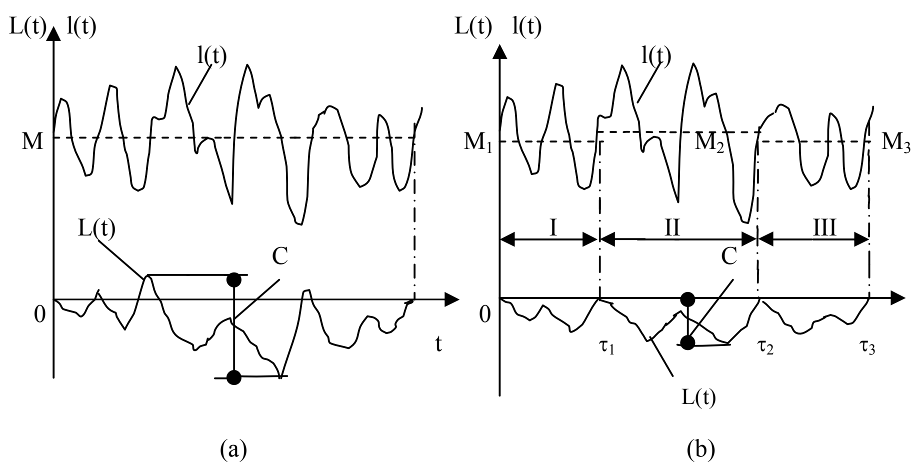

Figure 3. The load graphs of thermal energy system and the integral curves of accumulated thermal energy in different segmentation of the load cycle

$$L_k(t)=L_k(\tau_{i-1})+\frac{t-\tau_{i-1}}{\tau_i-\tau_{i-1}}\int_{\tau_{i-1}}^{\tau_i} l(t)dt-\int_{\tau_{i-1}}^{t} l(t)dt$$

$$=\frac{t-\tau_{i-1}}{\tau_i-\tau_{i-1}}\int_{\tau_{i-1}}^{\tau_i} l(t)dt-\int_{\tau_{i-1}}^{t} l(t)dt$$

$$\tau_{i-1}\le t\le\tau_i \text{ and } i=1,\ldots,N \tag{9}$$

Because it is often difficult to find out an expression of the load curve l(t) in a form of analytical function, the discretization of Eq. (9) may be a better way to simplify and quicken the calculation through Eq. (10).

$$L_k(j_{bi}, j_{ei}, j)=\frac{S}{R}\Big[\frac{j-j_{bi}+1}{j_{ei}-j_{bi}+1}\sum_{j=j_{bi}}^{j_{ei}} l(j)-\sum_{j=j_{bi}}^{j} l(j)\Big],$$

$$j_{bi}\le j\le j_{ei} \text{ and } i=1\ldots N \tag{10}$$

In Eq. (10), the whole period of a cycle, its length being S (hrs), is supposed to include R time cells. Thus, j = 1,…,R. Obviously, j_{bi} and j_{ei} denote the sequence numbers of time cells at the beginning and the end of the i-th segment respectively.

In consideration of the periodicity of the load curve, there will be R different load cycles if the time cell at the beginning of the original cycle moves down the cycle, i.e., the beginning point moves in sequence from the 1st time cell to the last (R-th) one. By using a subscript r added to $L_k(j_{bi}, j_{ei}, j)$ to distinguish various cycles, Eq. (10) takes the form as following:

$$L_{r,k}(j_{bi}, j_{ei}, j)=\frac{S}{R}\Big[\frac{j-j_{bi}+1}{j_{ei}-j_{bi}+1}\sum_{j=j_{bi}}^{j_{ei}} l(j)-\sum_{j=j_{bi}}^{j} l(j)\Big],$$

$$j_{bi}\le j\le j_{ei} \text{ and } i=1\ldots N \tag{11}$$

Usually, there must exist a minimum segment length permitted, represented by U (hrs), because of technical consideration. The value of U should be taken into account when the program is being designed according to the algorithm. Thus, K, the total number of possible patterns of segmentation of the load cycle corresponding to certain r can be calculated by Eq. (12).

The total number of possible segmentations will be K multiplied by R when various cycles are taken into account.

$$K=\begin{cases}1 & (N=1)\\ R-NUR/S+1 & (N=2)\\ \frac{1}{2}\sum_{P_{N-2}=1}^{R-NUR/S+1}\sum_{P_{N-3}=1}^{P_{N-2}}\cdots\sum_{P_2=1}^{N_3}\sum_{P_1=1}^{P_2}P_1(P_1+1) & (N\ge 3)\end{cases} \tag{12}$$

For the sake of simplification, use vectors:

$$\mathbf{j_b}=(\mathbf{j_{b1}},\ \ldots\ ,\mathbf{j_{bN}})^T \tag{13}$$

$$\mathbf{j_e}=(\mathbf{j_{e1}},\ \ldots\ ,\mathbf{j_{eN}})^T \tag{14}$$

$$\mathbf{L_{r,k}}(\mathbf{j_b}, \mathbf{j_e}, j)=[\mathbf{L_{r,k}}(\mathbf{j_{b1}}, \mathbf{j_{e1}}, j), .., \mathbf{L_{r,k}}(\mathbf{j_{bN}}, \mathbf{j_{eN}}, j)]^T \tag{15}$$

With certain values of N and U, the optimization problem for the minimum necessary capacity of TES can be expressed as following.

$$\begin{cases}\min C_{r,k}^{(U,N)}(j_b, j_e)=\max_j \mathbf{L_{r,k}}(\mathbf{j_b},\mathbf{j_e},j)-\min_j \mathbf{L_{r,k}}(\mathbf{j_b},\mathbf{j_e},j)\\ \quad \mathbf{j_b},\mathbf{j_e}\in E^N;\quad j=1,\cdots,R;\quad r=1,\cdots,R;\quad k=1,\cdots,K\\ \text{subject to } UR(i-1)/S\le j_{bi}\le R-UR(N-i+1)/S+1\\ \quad j_{b(i+1)}-j_{bi}-UR/L\ge 0, \qquad i=1,\cdots,N-1\\ \quad j_{b(i+1)}-j_{ei}-1=0, \qquad i=1,\cdots,N-1\\ \quad j_{eN}=R\end{cases} \tag{16}$$

The solution of programming (16) is ($\mathbf{j_b^*}, \mathbf{j_e^*}$),

$$\text{where}\quad \mathbf{j_b^*}=\begin{pmatrix}\mathbf{j_{b1}^*}\\ \mathbf{j_{b2}^*}\\ \vdots\\ \mathbf{j_{bN}^*}\end{pmatrix},\ \mathbf{j_e^*}=\begin{pmatrix}\mathbf{j_{e1}^*}\\ \mathbf{j_{e2}^*}\\ \vdots\\ \mathbf{j_{eN}^*}\end{pmatrix} \tag{17}$$

The corresponding value of the objective function, $C_{r,k}^{(U,N)}(\mathbf{j_b^*}, \mathbf{j_e^*})$, is then the minimum necessary capacity $C_{min}^{(U,N)}$ wanted.

The constrained nonlinear programming (16) is rather extraordinary, for its variables serve as the limits of integrals in the objective function that is, in addition, non-differentiable. In this case, the strategies for finding out the global optima of problem (16) can not on any account be those available and widely used approaches, including almost all theoretically based strategies. As there seems to be no alternative, some heuristically based strategies, i. e., function comparison or direct search methods: simplex search, polytope, or complex, may be developed to solve the particular problem, in spite of any limitation in their general usefulness (Gill et al., 1981; Reklaitis et al., 1983). Computation practices showed that an approach to exhaustive search proved to be effective and fruitful just due to the extraordinarity of the objective function. Thanks to powerful computers the minimum necessary capacity of TES can readily be computed through such a function comparison method.

The structure flowchart of the algorithm in brief

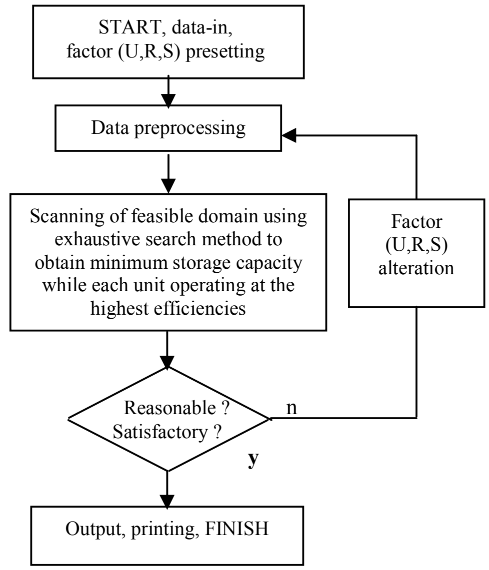

Figure 4. The flowchart of the algorithm

The computation model

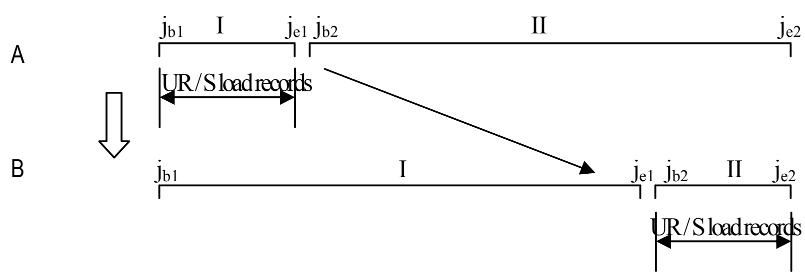

Figure 5. Basic procedure P(I,II)

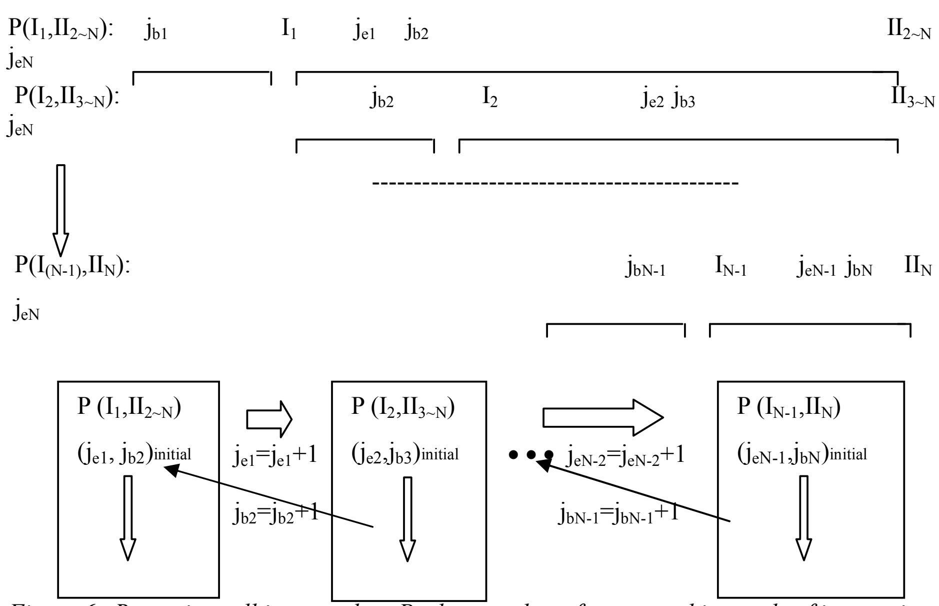

Figure 6. Recursive call in procedure P when number of segmented intervals of integration being N

There must be computation procedures covering the whole feasible domain. Now start with the simplest, the segmentations of only two segments within a cycle, and calculate the integrals repeatedly. *Figure 5* is the basic procedure, P(I,II). The segmentations of the cycle will exhaustively be enumerated by changing j_{e1} and j_{b2} from case A to case B simultaneously. The same processes will then be repeated one by one as the beginning time cell of the cycle moves from its initial position to the end of the original cycle.

The whole feasible domain of the problem can thus be covered by recursively calling in procedure P(I,II) while the beginning time cell of the cycle is changed from its initial position to the end of the original cycle if the cycle is divided into N segmented intervals for integration (*Figure 6*).

In consideration of Eqs. (18) and (19) that specify the constrained ranges of the first and last time cells of the i-th segment, it would not be difficult to perform the procedures described above

$$j_{bi} = 1+UR(i-1)/S \sim 1+R-UR(N-i+1)/S \qquad (18)$$

$$j_{ei} = i\,UR/S \sim R-UR(N-i)/S \qquad (19)$$

As an examination the program that was designed according to the algorithm was used to an existing boiler plant equipped with a steam accumulator at Shanghai Heavy Machine Works (SHMW). The steam accumulator of 155 m^3 was added to the steam supply system that had originally had a pulsating load curve (TABLE I) and was reported effective on saving fuel (Qu, 1997). By using the program, the computer read in the load curve with U = 3, and gave the results, i.e., the minimum necessary thermal capacities were 2.76 MJ and 2.51 MJ corresponding to N = 5 and 6 respectively. The minimum volumes of the steam accumulator would be 128 m^3 and 116 m^3 accordingly, being 17.4% and 25.2% less than that originally adopted (TABLE II). Meanwhile, the computer also offered proposals of optimized load distributions over various segments. According to the distributions, each boiler in the plant would operate within a range of load level resulting in the highest efficiencies.

4. An Example of the Capacity Optimization for TES

TABLE I DAILY STEAM LOAD OF SHMW

Time	1:00-2:00	2:00-3:00	3:00-4:00	4:00-5:00	5:00-6:00	6:00-7:00	7:00-8:00	8:00-9:00
Steam load (MJ/hr)	4.461	4.461	4.461	7.597	4.461	4.461	4.774	5.715
Time	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00
Steam load (MJ/hr)	5.715	5.402	4.774	5.715	8.852	5.402	4.474	7.597
Time	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	24:00-1:00
Steam load (MJ/hr)	4.461	4.461	4.461	4.461	7.597	4.461	4.461	4.461

TABLE II RESULTS OF THERMAL STORAGE COMPUTATION

	Capacity of TES (MJ)	Pressure of charge (MPa)	Pressure of discharge (MPa)	Volume of storage tank (m^3)
Values by SHMW	3.346	1.5	0.4	155
Values for N=6	2.51	1.5	0.4	116
Values for N=5	2.76	1.5	0.4	128

5. Conclusions

- Thermal energy storage is effective on increasing both the energetic and exergetic efficiencies of thermal energy systems, of which the loads are at low levels and frequently fluctuating with big amplitudes. In this case, it is economically reasonable to insert TES into small or medium-sized systems.
- Higher cost rates are one of the main barriers to the wider use of TES. However, by using optimization of TES capacity, this barrier could be broken down to a great extent.
- Example proves the algorithm and the program for the optimization of TES capacity fairly effective and fruitful.
- The program and algorithm can in principle be used not only in boiler plants, but also in other thermal systems where the load graphs are the same type as devoted in the paper. They may also be applied to optimal online control over systems where TES has already been set up.

Nomanclature

C	necessary capacity of TES (kJ)
D	difference between mean load and instantaneous load (kJ/h)
h	specific enthalpy (kJ/kg)
j	sequence number of discrete time cells within load cycle
K	total number of possible segmentations of load cycle
l	instantaneous load of energy system (kJ/h)
L	integral of difference D over t (kJ)
M	mean load over a cycle or any given period of time (kJ/h)
N	total number of segments in a load cycle
P	number
R	total number of time cells within a load cycle
s	specific entropy (kJ/kg)
S	length of a load cycle (h)
T	temperature (K)
t	time (h)
U	minimum length of a segment permitted (h)
V	lower heating value (kJ/kg)
ε	specific exergy (kJ/kg)
η	efficiency of boiler
τ	moment at the beginning or end of a segment (h)
ξ	factor

Subscript

b	beginning
e	end
en	energy
ex	exergy
f	fuel
fw	feedwater
i	sequence number of segments
k	sequence number marking different segmentations
m	mean thermodynamic
max	maximum
min	minimum
o	environmental state
r	sequence number distinguishing various cycles
st	steam

Superscript

N	total number of segments in a load cycle
U	minimum length of a segment permitted
*	solution

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