Modeling the basis power in the systems for continuous transport of fluids and bulk materials

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Abstract. This paper presents a novel developed model for calculating the totally useful power in the systems for continuous transport of fluids and bulk cargoes, allowing deeper and more functional analysis of the energy efficiency of this systems by physically based decomposition of the electricity consumption of a useful and unhelpful ingredient. The model consists of nine mathematical expressions by which, after determining the type of system, the physically required minimum possible power consumption can be calculated and compared with the total consumption. A pumping system for the transport of condensate water from a deaerator to the drum of a steam generator of a thermal power plant has been selected as the subject of the model demonstration experiment. In the investigation carried out, the basis power of the pumping system was 606.6 kW and the total losses were about 302 kW. Other energy efficiency indices have also been identified. The researches should be continued in the direction of algorithmization of the model and its justification mainly for the Type II systems.

1. Introduction

Globally, there are efforts to increase the efficiency of the energy consumption, which predetermines the need for a methodology that accurately determine the useful part of the consumed energy, based on the fact that the rapid development of the standards for more efficient equipment and components are pushing manufacturers towards further improvements on a component level [1]. In the cited paper, more than 30 energy efficiency measures were identified as it promotes a model to generate improvement suggestions, which can be compared with the strategies for reducing the industrial power consumption [2].

The importance of the energy efficiency of the industrial systems is obvious and related to the economic factors [3]. However, with the increase of the requirements for electrical efficiency, rise the need for more accurate measurement instruments, which must be sold [4]. That is why new approaches are required.

The systems for continuous transportation of fluids and bulk materials (SCTFB) have a large distribution without being targeted in a specific industry. Currently, there are several models to determine the useful part of the energy consumed. In many cases, the efficient part is assessed through the no-load condition of the system, which leads to inaccuracies in the evaluation. Other approaches are focused of the energy performance indicators, which presents a ratio between energy spent per unit of product, area, volume, or other quantity directly related to production [5].
Some papers examine the efficiency of machines with water-lifting applications [6, 7], which can be considered as subsystems of those described in this article and a comparison can be made to examine how much their efficiency can be improved. The topic is addressed in other works, such as the Journal of Cleaner Production article, which provides an overview of methods for developing better corrective measures for energy saving [8] or how losses in metallurgy can be reduced [9] or even how the estimated maintenance of facilities supports energy losses [10]. The energy efficiency not only in the cited, as well as other energy efficiency studies, is judged by the total power consumed by the system.

The aim of this study is to offer a model of the basis (fully useful) power in the SCTFB, allowing deeper and more functional analysis of the energy efficiency of this systems by physically based decomposition of the electricity consumption of a useful and unuseful component.

A pumping system for the transport of condensate water from a deaerator to the drum of a steam generator of a thermal power plant has been selected as the subject of the model demonstration experiment.

2. Theoretical model

2.1. Classification of the systems

The SCTFB are found in a number of industrial facilities such as thermal power plants, warehouses, ports, chemical plants, mines, quarries, water supply, irrigation and other flow systems.

This paper proposes a new classification of the systems under consideration. The systems are divided into those of the first and second type (Type I and Type II). After determining the type, the system can be categorized according to the transported load and denivelation. According to the cargo that is carried, the systems are for the transport of fluids – gases and liquids, and for transport of bulk materials. According to the denivelation, rising, horizontal and descending systems can be distinguished. Type I systems are those where the cargo-transport parameters (for bulk cargo – the speed, and for fluids – the pressure) are irrelevant and Type II are required for a certain load speed or pressure (figure 1).

![Diagram](https://via.placeholder.com/150)

**Figure 1.** Parametric-based classification of SCTFB.
2.2. Mathematical models

In the case of continuous bulk transport systems, the basis power is determined by the gravitational constant and the variable parameters mass \( m \), the difference in denivelation \( \Delta h \), the time \( t \). In the case of Type II systems, the desired load speed \( v \) at the output of the flow line is also considered. For Type I systems, the summary formula may be presented:

\[
P_b = \frac{m \cdot g \cdot \Delta h}{t},
\]

and for those of Type II:

\[
P_b = \frac{m \cdot g \cdot \Delta h}{t} + \frac{m \cdot v^2}{2t} = \frac{m}{t} \left( g \cdot \Delta h + \frac{v^2}{2} \right),
\]

where \( m \) is the mass of the load, \( g \) – the gravitational constant, \( t \) – time of transportation, \( \Delta h \) - the difference between the altitude at the starting and the end point of the system and \( v \) – the desired load speed at the end point.

In the case of continuous fluid transport systems, the basis power shall be determined by the first according to the fluid type - liquid or gas. When we replace in equation (2):

\[
Q = \frac{V}{t} = \frac{m}{\rho \cdot t} \Rightarrow m = Q \cdot \rho \cdot t,
\]

where \( V \) is the fluid volume, \( Q \) is the fluid flow rate, and \( \rho \) is the density of the load, the basis power of Type I fluid systems can be obtained:

\[
P_b = \frac{Q \cdot \rho \cdot t \cdot g \cdot \Delta h}{t} = Q \cdot \rho \cdot g \cdot \Delta h,
\]

and for those of the Type II:

\[
P_b = Q \cdot \rho \cdot t \cdot g \cdot \Delta h + Q \cdot \Delta p_T = Q \left( \rho \cdot t \cdot g \cdot \Delta h + \Delta p_T \right).
\]

In the case of gas transport systems, the difference in pressure \( \Delta p_T \) of the starting and the ending point of the system, as well as the load flow rate \( Q \) is essential:

\[
P_b = Q \cdot \Delta p_T.
\]

According to the denivelation, the systems in question are horizontal, rising and descending. In the case of horizontal systems of Type I, the basis power is zero, since starting from equation (1) at \( \Delta h = 0 \), \( P_b = 0 \). In the case of Type II for bulk materials:

\[
P_b = \frac{m \cdot v^2}{2t},
\]

where \( v \) is the desired load speed at the end point of transportation, which is also a determining factor. For the fluids, the desired output pressure and flow rate are critical and equation (6) applies.

In the case of the ascending systems, the general formulae set out above apply, as there is no case where \( \Delta h = 0 \), \( P_b = 0 \) for the Type I systems, and the determining factor is the difference \( \Delta h \) in the height of the starting and ending point. For Type II systems, in addition to the difference in denivelation \( \Delta h \), the desired initial parameters are also relevant. In this case for Type I systems, equation (1) applies for bulk cargoes, and equation (2) - to those of Type II. Equations (4) and (6) are in force for Type I lifting systems for liquids and fluids, and for Type II - equations (5) and (6), respectively.

Resulting from the gravitation, the basis power is zero in the case of descending systems of Type I. In the case of Type II systems, it is essential whether the necessary parameters are reached as a result of the mass of the load and the difference in the height of the starting and ending points of the system.
In the case of Type II bulk materials systems, based on the fact that the speed caused by the gravitation is:

\[ v_g = \sqrt{2gh}, \]  

if the desired output speed of the load is equal to that obtained from the physical parameters of the system, then the basis power is equal to zero \((P_b=0)\). Otherwise, \(\Delta v\) is defined as a difference between the desired speed \(v\) and the \(v_g\) obtained from the gravitational forces

\[ \Delta v = v - v_g, \]

as the basis power is:

\[ P_b = \frac{m\Delta v^2}{2t}. \]

Similarly for lowering systems in the transport of fluids and gases, if the desired pressure is equal to that obtained by the physical parameters of the system, the basis power is equal to zero or in the other case we define \(\Delta p = p - p_g\), as a difference between the desired pressure \(p\) and the pressure \(p_g\) obtained by the gravity. The basis power is:

\[ P_b = \Delta pQ. \]

### 3. Case study

#### 3.1. Object of investigation

A characteristic pumping system for transporting condensate water from the deaerator to the drum of a steam generator in a thermal power plant has been selected as a case-study object (figure 2).

![Figure 2](image)

**Figure 2.** Diagram of a feeding pump system in a steam power plant: D – drum; SH – superheater; FP – feeding pump; af – auxiliary feeding; DA – deaerator; CP – condensate pump.

According to the proposed classification, the investigation object is a lifting system for continuous transport of fluids of Type II. The system consists of a deaerator, a power pump, after which two loops are distinguished – to the drum and to an auxiliary feeding, serving to provide different auxiliary processes from the water tract of the plant. A series of connected water heaters have significant influence on the hydraulic resistance of the track. On the other hand, the hydraulic resistance of the contour is dictated by the passage through the heated high pressure and the eco-oiler of the steam generator. The differences in the geodetic heights at which the water rises are determined by the
elevations. The power pump is powered by an induction motor with a rated voltage of 6000 V. The rest parameters of the motor are: type 32V-188-02H; nominal power 2000 kW; nominal current 227 A; rotor speed 2975 min⁻¹; power factor 0.88; efficiency 96 %.

3.2. Results
The results are obtained using the methods described in [11]. The investigation methodology is complemented by the mathematical model in section 2.2.

The pump flow rate is taken from the monitoring system of the plant. The data is for a characteristic steam generator operation for a period of 1 hour and 7 minutes, with a sampling interval of 1 minute. The flow rate is almost constant. The average flow rate was 0.0461 m³/s. The other parameters in the observations carried out are \( \Delta p = 1.3 \times 10^7 \) Pa; \( \Delta h = 13.3 \) m, \( \rho = 1000 \) kg/m³. Using these output data, the pump's basis power equals to 606.6 kW. The study also determined that the average measured power is 908.7 kW. Thus, the level of total losses can be easily specified as the difference between the power consumed and the basis power. In this case, the total losses are about 302 kW. The rest energy efficiency indices are presented in table 1.

| A1  | A2  | A3  | A4  | A5  | A6  | B1        |
|-----|-----|-----|-----|-----|-----|-----------|
| kW  | kVar| kW  | kW  | kW  |     | kW       |
| 1666.65 | 944.53 | 47.7 | 144.1 | 792.61 | 1.222 | 908.7     |
| B2  | B3  | B4  | B5  | B6  | B7  | C2        |
| kW  | kW  | kW  | kW  | kW  |     | kW       |
| 501.3 | 67  | 649.06 | 323.25 | 972.31 | 1.498 | 302.1     |
| D1  | D2  | D3  | D4  | E1  | E2  | E3        |
| kW  | kW  | kW  | kW  | kW  | kW  | kW       |
| 1.23 | 2.24 | 19.3 | 179.7 | 0  | 0.4  | 96        |
| E4  | E5  | E6  | F1  | F2  | F3  | F4        |
| kW  | kW  | kW  | kW  | kW  | kW  | kW       |
| 0   | 0.01 | 0.87 | 12.26 | 0.014 | 12.04 | 0.024     |

The indices used in table 1 are as it follows: A1 - active power in optimum operation; A2 - reactive power in optimum operation; A3 - optimum operating time; A4 - non-useful electric power consumption in optimum operation; A5 - total electric power consumption in optimum operation; A6 - relative electric power consumption in optimum operation; B1 - average active power in actual operation; B2 - average reactive power in actual operation; B3 - actual operating time; B4 - useful electric power consumption; B5 - non-useful electric power consumption in actual operation; B6 - total electric power consumption in actual operation; B7 - relative electric power consumption in actual operation; C2 - total power loss; D1 - coefficient of overrun of total energy consumed; D2 - coefficient of overrun of non-useful energy consumed; D3 - overrun of operating time; D4 - overrun of electric energy; E1 - deviation from the maximum electric motor efficiency in optimum operation; E2 - deviation from the maximum electric motor efficiency in actual operation; E3 - maximum electric motor efficiency; E4 - deviation of the power factor from the desired value in optimum operation; E5 - deviation of the power factor from the desired value in actual operation; E6 - desired power factor; F1 - standard deviation of the active power in actual operation; F2 - coefficient of variation of the active power in actual operation; F3 - standard deviation of the reactive power in actual operation; F4 - coefficient of variation of the reactive power in actual operation [11].

The primary energy-efficiency indices are B7, D1 and D2. They give information for essential analysis. B7 is always higher than 1 and it is equal to 1 for an ideal transport system. In this case, the index is equal to 1.498 relative units. This means that per each 1 kWh energy consumed for making useful work, the pump system consumes additional 0.498 kWh for covering the losses. On another
hand, if \( D_2 \) is higher than \( D_1 \), the energy efficiency can be best increased by improving the working condition instead of making constructional changes. And vice versa.

From the value of \( D_1 \) equal to 1.23 and the relatively small value of \( A_6 \), a satisfactory structural perfection of the pump is shown. The values for actual mode of operation are statistically reliable. This is confirmed by the low coefficients of variation of about one and two percent.

Based on the coefficient \( D_2 \) and on the difference between \( A_6 \) and \( B_7 \), which is 0.3 relative units, it can be concluded that there is an opportunity to improve the operating conditions of the pump by additional loading until it reaches the optimal level. This improvement can lead to savings of nearly 180 kWh of electricity (index \( D_4 \)). Given the continuous pump operation, the economy for a month reaches EUR 6 500 in average production price of EUR 50/MWh.

4. Discussion
This paper proposes a new way to determine the theoretically necessary, minimum possible electricity consumption by a basis power modelling method. In the case of the systems for continuous transport, the basis power modelling is an appropriate approach for calculating the minimum energy needed to operate and improve them. The developed method can also be applied to the construction of new systems with the best possible parameters, which would have both a greater environmental and economic effect.

The actual consumption is the total energy consumed and is determined by the power actually consumed from the network. The basis power level predetermines the amount of energy that has been spent solely to carry out a useful work. The difference between the actual electricity consumption and the energy determined by the basis power gives the total losses. The total losses level characterises the constructive perfection and the appropriate operating mode of the systems.

On the other hand, some pieces of research published at the time identified the efficiency of the systems as the ratio of the difference between the total energy consumed and the energy determined by the no-load power to the total electricity consumed. It should be considered that this approach does not take into account the variable losses component and the efficiency determined by the no-load level is not sufficiently reliable.

The method developed in this study allows to identify clearly and precisely this minimally needed energy and to compare it with the amount spent. This gains a better understanding of the total losses. The example with the pumping system above shows that approximately 1/3 of the energy is lost in the field. This makes clear that there are significant possibilities for optimizing the systems.

5. Conclusions
A new classification has been developed for bulk materials and fluid transport systems, through which the system type can be unambiguously determined.

An aggregate model including nine mathematical expressions is derived, by which, after determining the type of system, the required minimum possible power can be physically-based calculated and compared with the total consumption. The model can be used both in existing systems and when planning new ones.

The proposed methodology is demonstrated in a real working environment by setting the basis power for a rising system for continuous transport of fluids of Type II, part of a thermal power plant. On the basis of the proposed model, it is possible to plan optimizations of the systems environmentally and economically.

Future research covers: algorithmizing the model and developing relevant software products to computer-aided research; justification of the applicability of the model to the rising, horizontal and descending systems for the continuous transport of bulk materials of Type I and Type II, as well as to the Type I fluid systems.

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