TRANSPORT-STORAGE SYSTEM OPTIMIZATION IN TERMS OF EXERGY

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ABSTRACT

The paper presents possibilities of transport-storage system optimization which takes into account energy everywhere where it and its exchange occur. It is assumed that the transport-storage system is a logistic system component and it consist of a building, spaces (with or without racks) where cargo units are stored, equipment for transferring the cargo units and personnel operating the equipment and working physically. The optimization includes integration components: a storage technology with internal transport and information interchange.

Keywords: logistics, transport-storage system

1. INTRODUCTION

The amount of energy consumed by technical systems to perform the required functions and processes is a major consideration in every sphere of economic activity. For this reason the consumption of fuels, natural gas, electricity and heat is being monitored. Currently, filament lamps are being replaced by fluorescent lamps. Also combined thermal and electrical energy management, i.e. cogeneration, is being introduced. Now it is important not only how much waste is produced or how high the recycling level is but also how much noise a technical system generates, what the environmental (thermal and harmful emission) loading during its life is and to what extent the system will burden the environment when its life ends. Automotive companies already at the car design stage decide which of the parts can be used again in a new vehicle once the life cycle ends Lewandowska (2008), Szargut (2007), Szargut (1965).

Energy savings are sought in all places where energy and its exchange occur, including logistic systems. It is assumed that a store as a transport-storage (T-S) system and a logistic system component consists of a building, spaces (with or without racks) where cargo units are stored, equipment for transferring the cargo units and an information interchange subsystem consisting of an automatic identification system and a storage management support system Korzen (1997), Korzen (1999). Besides human labour, forklift trucks, conveyors and staplers are used to transfer cargo units.

The particular processes require energy investments depending on the automatic identification and electronic data information interchange systems. The energy investments can be conveniently determined using the physical dependencies between energy, work and power.

2. EXERGY

Up till now the efficiency of energy conversion processes has been investigated through energy analysis, i.e. exclusively on the basis of the first law of thermodynamics. The energy balance treats all the forms of energy equally, without taking into account their unequal quality (practical usefulness). But it is obvious that 1 kJ of electric energy generated by a power plant is much more useful than 1 kJ of energy carried by water used for cooling the power plant. Besides, electric energy has a much higher economic value. Hence it can be assumed that electric energy and mechanical work are characterized by the highest practical usefulness and one can obtain from them any other form of energy in an equivalent amount.

The cost of producing useful energy increases as the thermodynamic processes advance. This is due to the fact that the amount of useful exergy decreases because of unavoidable losses in the irreversible processes. Moreover, at each process step an additional cost of the necessary investments appears.

The exergy of a system is always non-negative. It is equal to zero when the system is in thermodynamic equilibrium with the environment and it increases with the degree of departure from this equilibrium. The value of the system's exergy depends on both its state and the state of the environment. The energy conversion optimization problem can be formulated as an endeavour to minimize exergy losses as expressed by the ratio of the energy supplied to an actual device to the energy supplied to the ideal device, and needed to perform the same work by the respective devices.

An exergetic analysis can be a major component of a more comprehensive multifactor analysis, such as LCA (life cycle analysis), LCEA (life cycle exergy analysis, e.g. Finnveden & Ostlund) and ELCA (exergetic life cycle analysis, Cornelissen) Lewandowska (2008), Szargut (2007).

Considering the above, it is no longer enough to take into account only cost and technical factors when selecting transport-storage system components. One can say that this would be highly insufficient.

The hitherto experience indicates that it is difficult to correct errors made at the design stage, whereby the operating costs keep increasing. According to the current views on this subject, a qualitative assessment of the operating costs of products or more broadly, technical systems at the design stage should involve: a model of system operational quality assurance, an investor promotional strategy concerning the operational values of the system being created, the group qualification of the system, stemming from the adopted pragmatics of its operation.

Operational worthiness is a technical consideration for mainly the designer optimizing the system to obtain the minimum costs of its construction and lowering its quality only to a degree which will not adversely affect its performance and will not result in the lodging of complaints by the investor. In addition, one should optimize the transport-storage logistic system from the point of view its function (the proper choice of system components), which will contribute to the satisfaction of the investor who expects solutions minimizing operating costs as wells increasing safety and reliability. The technical, economic and social (ergological, ecological, safety) considerations are reconciled in the universally adopted Quality Standards. A technical system should also be assigned to a proper technical system classification group. Transport-storage logistic systems are usually placed in the group: “a system designed in such a way that its structural components can be replaced during preventive maintenance”.

Despite the above determinants, design solutions are often based on the particular producer’s intuition or many-year experience in the creation of systems for the average investor. The world trends indicate that the lifetime of technical systems continuously decreases and the interest in new generations of transport-storage systems steadily grows. At the same time as a result of the technological progress new systems are mostly created not through a significant improvement (based on conclusions drawn from operational experience) of the existing solutions, but through a general change of the system concept/philosophy because of new ergonomic, ecological, energy saving, work humanization, robotization, etc., requirements Korzen (1997), Korzen (1999).

The consequences of a system’s potential behaviour and its operational effects should be foreseen already at the design stage and taken into account at the implementation stage.

Application of exergy in calculation of t-s systems

The whole exergy of a system can be divided into the following components: potential exergy, kinetic exergy, physical exergy, chemical exergy, nuclear exergy and other (e.g. connected with electromagnetic interaction, surface tension, etc.). For the investigation of the processes taking place in power equipment it is usually enough to take into account physical exergy and chemical exergy and if need be, kinetic exergy and potential exergy Urlich (1999).

$$B = B_f + B_{ch} + B_p + B_k \tag{1}$$

where:

B_f - physical exergy,

B_{ch} - chemical exergy,

B_p - potential exergy,

B_k - kinetic exergy.

Physical exergy is expressed by:

$$B_f = U - U_{ot} + (S - S_{ot})T_{ot} - p_{ot}(V - V_{ot}) \tag{2}$$

where:

U - internal energy,

S - entropy,

V - the system volume in a given state,

Uot, - internal energy,

Sot - entropy,

Vot - the system volume in a state of limited thermodynamic equilibrium with the environment, i.e. for the environment pressure and temperature (pot, Tot).

for a thermodynamic fluid

$$B_f = I - I_{ot} - (S - S_{ot})T_{ot} \tag{3}$$

where:

I - the enthalpy of the thermodynamic fluid in a given state,

I_{ot} - the enthalpy of the fluid in a given state and at the pressure and temperature of the environment.

imparted with work

$$B_f = W \tag{4}$$

Imparted with heat Q drawn from a source with constant temperature Tzc>Tot

$$B_f = Q\frac{T_{zc} - T_{ot}}{T_{zc}} \tag{5}$$

(it is equal to the work given up by the Carnot engine operating between heat sources with temperatures Tzc and Tot)

Imparted with heat Q drawn from a source with constant temperature Tzc<Tot

$$B_f = Q\frac{T_{ot} - T_{zc}}{T_{zc}} \tag{6}$$

(it is equal to the minimum work which should be supplied to transport heat Q, drawn from source with temperature Tzc, to the environment, i.e. equal to the work drawn by a left-running Carnot cycle operating between heat sources with temperatures Tzc and Tot)

Chemical exergy:

$$B_{ch} = \sum_i N_i(\mu_i - \mu_{iot}) \qquad (7)$$

where:

N_i - the amount of moles in the i-th substance,,

μ_i and μ_{iot} - chemical potentials of the i-th substance in respectively the system and the environment.

Chemical exergy is equal to the maximum work which can be obtained when a considered substance passes from the state of limited equilibrium with the environment to the state of full thermodynamic (thermal, mechanical and chemical) equilibrium. In cases when the substance whose chemical exergy is to be determined does not occur in the environment, when calculating exergy one takes into account a chemical reaction whose products belong to the common components of the environment.

3. ANALYTICAL MODEL OF T-S SYSTEM

A closer analysis shows that in actual processes energy is not lost (we do not have in mind the energy conservation law here), but it is converted to another form, less suitable for sustaining the processes. An example here is the process of removing a pallet from the truck's floor in the cargo handling area at the entrance to the storehouse and placing it in a rack slot on the selected level. The energy spent on transporting the pallet vertically is partially recovered when the latter is being removed from the rack, minus only the energy needed to lift the fork carriage again. In this process the pallet acts as an energy accumulator.

For the exemplary store shown schematically in fig. 1 energy Q [Wh] is calculated from this equation

$$Q = Q_d + Q_w + Q_L + Q_V + Q_{ah} + Q_{Ma} + Q_{Me} + Q_S \qquad (8)$$

where:

Q_d – the heat penetrating through the walls, ceiling and floor of the cold room;

Q_w – the heat removed from the merchandise;

Q_L – the heat given up by the air unintentionally brought into the cold room;

Q_V – the heat generated by the operating air cooler fan;

Q_{ah} – if need be, the heat generated during defrosting;

Q_{Ma}– the heat emitted by the lighting, the machines and similar equipment in the store;

Q_{Me}– the heat emitted by people;

Q_S – the heat constituting a standby in case of unforeseen changes in the store's thermal load.

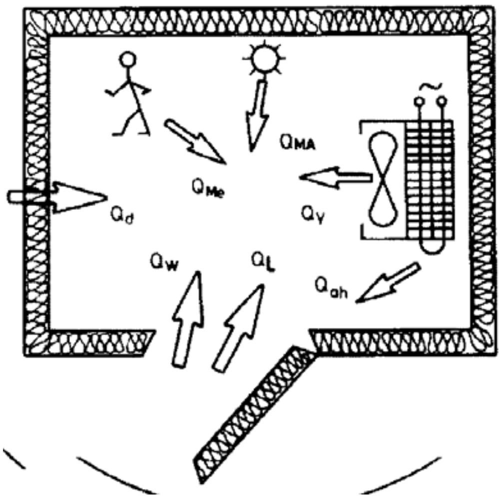

Fig. 1. Energy balance in exemplary store.

Equation (8) does not take into account, for instance, the heat which could be recovered through ventilation by proper equipment and directed to heat receivers. Moreover, the heat of condensation, generated during the operation of the refrigerating system (fig. 1) is regarded as waste heat, but it could be sufficient to heat service water in, for example, a transport-storage system consisting of a freezer and an abattoir. One can imagine the side-by-side operation of an abattoir which uses the energy remaining from the operation of a freezer (a cold store in some cases) to heat up service water for production purposes.

Taking into account the above considerations, a new approach to the optimization of transport-storage systems is needed. In the literature on the subject one can find multicriterial methods for the optimization of the drive/transfer routes Korzen (1997), Korzen (1999). Hence there is a need to introduce a new parameter to describe the energy conversions involved.

It is assumed that in a model case the cargo unit is on a semitrailer from where it is taken by a forklift truck in the cargo handling area at the entrance to the storehouse. Then it is transported to the identification point and to a power-driven roller conveyor which transfers the cargo unit to the face of the high-storage zone and to the stapler's delivery-reception area. The automatically controlled stapler places the cargo unit in the rack slot with the indicated location address. The process of release from store proceeds similarly but in reverse Lewandowska (2008), Szargut (2007).

The collection of a pallet by a forklift truck or a stapler involves covering a distance and energy expenditure on lifting or lowering the pallet (including forking). In order to simplify the model, it is assumed that the energy expended on lifting the pallet is recovered in the process of its lowering, but this applies to only electric forklift trucks.

For a forklift truck the energy needed to lift a pallet from a conveyor is expressed by formula (9). The energy needed to shift the empty fork (Es) is expressed by a similar formula (the pallet weight is subtracted from weigh m). A proper fork carriage weight should be assumed for each forklift truck.

$$E_p = m \cdot g \cdot h \qquad (9)$$

where:
m - the weight of the pallet and the fork,
g - gravitational acceleration,
delta h - a height difference.

The energy needed to cover the forklift truck distance (with or without a cargo unit) is calculated from equation (10), assuming that the forklift truck resistance force must be overcome by a proper amount of kinetic energy. The type of forklift truck drive (diesel, electric) is taken into account.

$$E_K = R_L = \left(\xi + 0{,}15 \cdot \frac{V}{10}\right) \cdot G_L + 150 \cdot \chi + 3{,}5 \cdot \frac{V^2}{10} \qquad (10)$$

where:
ξ – a resistance coefficient,
V – speed,
G_L – engine weight,
χ – the number of truck axles.

In the case of a stapler, the particular components of its work cycle are modelled similarly as for the forklift truck.

The energy needed to service the pallet by the forklift truck in the transport-storage system is expressed by this equation

$$E_E = E_P + E_S + E_Z + E_C + E_W \qquad (11)$$

where:
E_P - the energy needed to lift a pallet with a cargo unit,
E_S - the energy expended to lift the empty fork carriage,
E_Z - the energy needed to carry the pallet with the cargo unit,
E_C - the energy needed for the passage of the truck without the cargo unit,
E_W - the energy expended on forking.

Since, as opposed to transport by forklift trucks and staplers, the pallet transported by a (roller) conveyor does not change its potential energy during the whole duration of the transport (and only a change of this energy is considered to be work), the whole electrical power of the conveyor drive converts to the energy expended to overcome the resistance to motion of the transporting device.

Ideally, in a transport-storage system there should be energy needed to perform work, e.g. to convey a pallet from one place to another in the transport-storage system. When this task is executed, a certain amount of energy arises which is simply wasted. It is assumed that this energy is exclusively thermal energy. It can be estimated using formulas (12), (13) and (14).

The heat brought in with fresh air is calculated from this equation

$$Q_P = n \cdot V \cdot \rho \cdot \Delta h \qquad (12)$$

where:
n - an air change coefficient [1/day],
V - storage volume [m3],
ρ - air density [kg/m3],
Δh - a difference in air specific enthalpy [KJ/kg].

The heat generated by the lighting is expressed by this relation

$$Q_{os} = n \cdot q_{os} \qquad (13)$$

where:
n - the number of lighting units,
Q_{os} - the unit power of the installed lighting depending on the illuminance and kind of lighting [W].

The heat generated by the forklift trucks, the staplers and the conveyors is expressed by this relation:

$$Q_V = n \cdot P \cdot (1 - \mu) \qquad (14)$$

where:
n - the number of forklift trucks/stapler/conveyors,
P - the power applied to the device [W],
μ - the factor of the power needed to transport the cargo unit.

The heat generated by the personnel working in the store is expressed by this relation:

$$Q_L = n \cdot q_M \qquad (15)$$

where:
n - the number of persons present in the store,
q_M - the flux of thermal energy generated by a single person [W].

On the basis of the energy consumption (including the consumption of electric energy, diesel fuel or gas, etc.) data for a typical transport-storage system one can calculate the amount of energy needed to obtain the desired effects, i.e. the energy expenditure per cargo unit (e.g. the europallet) in the transport-storage system.

For a transport-storage system in which pallets from the cargo handling area are collected by a forklift truck, transported to a roller conveyor, transferred to a stapler and placed by the latter in a rack slot, the system capacity is 12 europallets per hour. Exemplary results of calculations for such a system, using the model shown in fig. 2, are presented below.

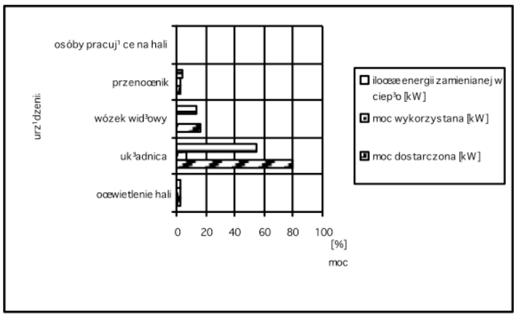

Fig. 2. Energy conversion relationships for transport-storage system. (personnel working in storeroom, conveyor, forklift truck, stapler, storeroom lighting, equipment, amount of energy converted into heat, used up power, applied power, power)

The diagram shows that a forklift truck equipped with a 4 kW engine, working in the transport-storage system, generates 3.4 kW of heat and its capacity factor is about 0.15 (the forklift truck is exceptionally badly matched). In the set of staplers this coefficient is slightly better – amounting to 0.31. In addition, the particular devices generate about 77 kW of heat. This information can be useful for the storehouse manager with regard to the selection of heating or air conditioning systems (or refrigerating units in the case of freezers). By evaluating the appropriateness of a logistic system from the energy point of view one can manage it properly, i.e. assign tasks to the particular devices.

In papers Korzen (1997) and Korzen (1999) it is suggested to take into account the following factors in an evaluation of transport-storage system appropriateness (the optimum choice of system components):

- the storage area utilization factor,
- the storage space utilization factor, etc.,
- the cost of passage of a single pallet through the store.

It is also proposed to introduce another factor – the energy consumption for the passage of a single cargo unit through the store – calculated from this formula

$$\zeta = \frac{\sum E_{delivered} - \sum Q}{\eta} \qquad (16)$$

where:

$\sum Q$ - the sum of heat yield [Wh],

η - the capacity of the transport-storage system [units.].

One can also assume a certain interval of parameter ζ. for which the optimization of the transport-storage system will not raise any reservations.

4. CONCLUSION

The benefits of an exergetic analysis are:

Unlike energy efficiencies, exergy efficiencies constitute an easy to evaluate and interpret measure of system excellence.

By calculating energy losses for the particular links of a complex system one can indentify the degree, causes and location of its imperfections. Thus an exergetic analysis is particularly useful for solving optimization problems.

Exergy is a universal measure of the practical usefulness of the different forms of energy and so it is particularly suitable for the analysis of complex systems.

An exergetic analysis (as a component of LCA) can significantly help in the assessment of the effect of a given process on the natural environment and also in the evaluation of the economic aspects (thermoeconomics, exergoeconomics). By reducing exergy losses one can reduce the operating costs of equipment, but this usually entails an increase in investment expenditures.

A major factor affecting energy consumption, but not automatically included in the presented transport-storage system model, is the way in which information directly relating to the management of the analyzed transport-storage system is transmitted. This is reflected in the number of kilometres driven by the forklift truck depending on the terminal used: a mobile radio terminal, a terminal with base station or a stationary terminal. In the latter case, information in a transport-storage system is usually printed on paper, which requires direct contact between the forklift truck operator and the storehouse manager.

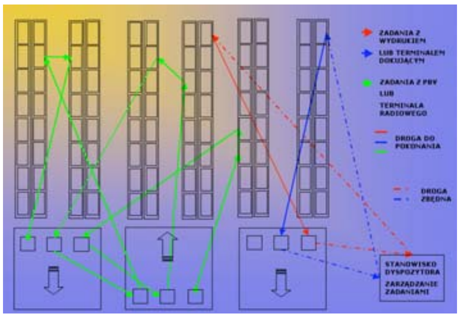

Fig. 3. Use of terminals in transport-storage systems. (tasks with printout or docking terminal, tasks with PBV or radio terminal, distance to cover, unnecessary distance, dispatcher station, management of tasks)

Storehouse operation with the use of: a (radio) terminal without a base station, a terminal with a base station, and a traditional system with a printout (a stationary scanner) is marked by respectively green, blue and red.

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