Improving Energy Efficiency of Pneumatic Handling Systems

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Abstract

This paper proposes an approach for the investigation and improvement of the energy efficiency of pneumatic handling systems. A new aspect in this paper is that the analysis is not only based on the compressed air consumption of pneumatic systems but on the balancing of energies. This strategy enables the continuous balancing of all fractions of energy and energy losses. Thereby the foundations to detect and address energy saving potentials can be laid.

In this article the energy distribution within a typical standard pneumatic handling system is analysed based on a gauging and simulation-based method. The results are used for the identification of energy saving potentials. With regard to the identified saving potentials adequate energy saving measures can be selected. In the first instance these measures are tested via simulation. Then they are implemented at selected pneumatic drives of the handling system for the purpose of validation. The experimental comparison of the energy consumption of the handling system before and after the modification shows energy savings amounting to 23%.

KEYWORDS: energy efficiency, pneumatics, pneumatic handling systems, energy saving potentials

1. Introduction

The field of industrial automation requires the realization of complex handling tasks. In order to solve said handling tasks handling systems with pneumatic and electric drives are being used. Pneumatic drives require only low investment and maintenance costs and distinguish themselves through a flexible and robust design. Today's standard pneumatic systems often cause relatively high costs incurred by energy consumption, because such systems are designed with respect to functionality not energy efficiency.

However, as proven by various studies /1/, /2/, today's compressed-air systems and pneumatic systems hold significant energy-saving potentials. In order to remain competitive these saving potentials must be utilized in the near future to improve the energy efficiency of pneumatic systems. The energetic analysis and improvement of energy efficiency of pneumatic systems is one of the focal points of research conducted at the Institute of Fluid Power at TU Dresden.

The aim of this paper is the systematic investigation and improvement of the energy efficiency of pneumatic multi-axes systems with regard to the thermodynamic correlations showing a close-to-practical-reality approach. The detailed approach shall be demonstrated using a standard pneumatic handling system more precisely an automatic placement machine which is used for the placement and quality check of plug housings. Using a simulation-based analysis of the energy distribution the recognition of energy losses and identification of energy saving potentials is achieved. For the drive systems with the most extensive energy requirements structural and parametric optimizations are performed. The resulting savings are experimentally substantiated.

2. State of research – energy efficiency of pneumatic systems

Pneumatic handling systems are multi-axes systems with various pneumatic drives. These systems are part of an entire industrial compressed air system. As shown in **Figure 1** a compressed air system consists of the three subsystems: Generation (compressor, filtration), distribution and consumption of compressed air (actuators). Each of these subsystems poses as its own field of research for the improvement of energy efficiency.



Figure 1: Structure of an industrial compressed air system

A cross-field study of energy consumption of compressed air systems has been conducted as part of the EU-study ", Compressed Air Systems in the European Union" /1/ and the campaign ", Druckluft effizient" /2/. With the help of random sampling investigations the total energy consumption of industrial compressed air systems in the European Union as well as energy saving potentials of these systems was empirically determined in /1/. The most significant energy saving potentials in compressed air systems identified by this study are the reduction of leakage (16%) and the overall system design including multi-pressure systems (4,5%). In /2/ cost- and energy-saving potentials could be identified by means of analysis of compressed air systems in different companies.

In the area of consumption systems different energy saving measures concerning dimensioning as well as pneumatic structure, valve technology and control strategy are known. Part of the measures regarding to valve technology are energy-saving circuit concepts like expansion- and exhaust-air recovery circuits as described in /3/ and /4/. These pneumatic circuit configurations serve to utilize exhaust air which in case of standard configurations is vented unused. Further circuit- and control-based measures aim at the modification of control- and valve technology pursuing the goal of minimizing fundamental losses at cylinder drives. Among these are for example pressure losses due to the use of exhaust-air flow controlling, energy emitted through exhaust air or waste heat during compression processes with high pressure level. The studies /4/ and /5/ focus on circuit configurations consisting of several 2/2-directional valves. Using switching valves and a PWM Control System (Pulse Width Modulation) a structure with

meter-in and meter-out control can be realized. By means of an optimized controlling strategy of the valves (reference /5/) the energy requirements of a drive system can be significantly improved.

A multitude of energy saving measures are known, however frequently concrete information regarding the correlation of energy saving potentials and implementation costs of the respective measure are amiss. In order to implement such energy saving measures in pneumatic systems the energy distribution within the system and the energy saving potentials must be known. In the subsystem of compressed air generation the thermodynamic accounting equations were derived in /6/ for the compression processes at a compressor and the degree of effectiveness was determined under various operating parameters. The thermodynamic approach for analyzing the energy distribution within pneumatic multi-axes systems has not yet been investigated.

3. Theoretical approach for energy balancing within pneumatic systems

In order to formulate the energetic balancing equations the system boundaries of the automatic placement machine has to be described at first. The dotted line in Figure 1 represents the system boundaries of the machine. Figure 2 displays schematically the pneumatic structure as well as the energy flow within the automatic placement machine under investigation. The system posses a compressed air supply (1), a service unit (2), tubing (3), valve terminals (4) and different actuators (5). A total of 34 cylinder drives, a vacuum ejector and a check nozzle are present. The solenoids of the directional valves are being controlled via a programmable logic controller (6). This structure generally matches that of a handling system. For the balancing, all energies that are important for the functionality of the pneumatic drive systems are being taken into account. At the compressed air supply the pneumatic energy flow $\dot{E}_{pn,su}$ enters the system. A part of this energy is transformed into mechanical power \dot{W}_{t} at the actors. The solenoids of the directional valves absorb electric energy flow \dot{E}_{el} . The pneumatic energy flow $\dot{E}_{pn,ex}$ is vented in the form of exhaust air at the directional valves. Through compression processes and friction within the system heat Q is created which dissipates to the ambience. However during expansion processes heat can also be absorbed from the ambience. Through the leakage occurring in the system the pneumatic energy flow $\dot{E}_{pn,I}$ is emitted via the leakage mass flow.



Figure 2: Pneumatic structure and energy flow within the automatic placement machine Pneumatic handling systems are open thermodynamic systems like gas turbines or compressors. The balancing of energies is usually done by analyzing the energy flow at an observation point within a time cycle or by balancing the energy flows between two observation points in a control volume with constant boundary conditions (stationary flow process). In case of pneumatic drive systems it is necessary to balance the energy flows between two observation points in a control volume but with changing boundary conditions (transient flow process). Thereby the time integrals of the energy flows within a time cycle have to be used. The equations for energy flow balancing are based on the first and second law of thermodynamics /7/. Energy is the sum of exergy and anergy. Contrary to anergy, exergy can be used for the transformation into work. By means of entropy production, the amount of anergy within a system increases.

For a complete balancing of the energies various observation points have to be established (ref. **Figure 3**). The observation points are to be selected in such a manner that the distribution of mass flows can be determined and all pressure drops as well as temperature changes at the various components can be recorded. Handling systems most frequently possess a great number of drives making the required number of observation points rather high. Figure 3 shows the balancing equations for a transient flow process at a control volume between two observation points based on the explanation in /7/.



Figure 3: Balance equations at the control volume of a piston chamber

In order to evaluate the exergy consumption of a pneumatic system the input exergy E_{ex} absorbed with the mass flow \dot{m}_{in} as shown in Figure 3 has to be determined in a certain time cycle.

$$\boldsymbol{E}_{\text{ex}} = \int \dot{\boldsymbol{m}}_{\text{in}} \cdot \left(\boldsymbol{h}_{\text{in}} + \frac{\boldsymbol{c}_{\text{in}}^2}{2} + \boldsymbol{g} \cdot \boldsymbol{z}_{\text{in}} - \boldsymbol{T}_0 \boldsymbol{s}_{\text{in}} \right) \cdot \boldsymbol{dt}$$
(1)

Due to the low flow velocities (c<15m/s) within the tubes and components of the handling systems, the kinetic energy carried along by the mass flow is negligible. The amount of potential energy is also very few in number and can be neglected as well. As a result the input exergy equation (1) simplifies to:

$$\boldsymbol{E}_{ex} = \int \dot{\boldsymbol{m}}_{in} \cdot \left(\boldsymbol{h}_{in} - \boldsymbol{T}_{0}\boldsymbol{s}_{in}\right) \cdot \boldsymbol{dt} = \int \dot{\boldsymbol{m}}_{in} \cdot \left(\boldsymbol{c}_{v} \cdot \boldsymbol{T}_{in} + \boldsymbol{p}_{in}\boldsymbol{v}_{in} - \boldsymbol{T}_{0}\boldsymbol{s}_{in}\right) \cdot \boldsymbol{dt}$$
(2)

The total energy consumption $E_{pn,su}$ of the handling system is determined at the service unit (obs. point 1) via the enthalpy consumption $\dot{m}_{su} \cdot h_{su}$. Under the assumption that there is an isothermal compression process at the compressor and no leakage as well as no pressure drops in the pipe network the exergy at obs. point 1 can be calculated:

$$\boldsymbol{E}_{\text{ex,1}} = \int \dot{\boldsymbol{m}}_{\text{su}} \cdot \left(\boldsymbol{h}_{\text{su}} - \boldsymbol{h}_{0}\right) - \dot{\boldsymbol{m}}_{\text{su}} \cdot \boldsymbol{T}_{0} \cdot \left(\boldsymbol{c}_{p} \ln\left(\frac{\boldsymbol{T}_{\text{su}}}{\boldsymbol{T}_{0}}\right) - \boldsymbol{R} \ln\left(\frac{\boldsymbol{p}_{\text{su}}}{\boldsymbol{p}_{0}}\right)\right) \cdot \boldsymbol{dt}$$
(3)

The volume of the compressed air network without and within the system is relatively large, resulting in a continuous temperature equalization. The temperature of the

compressed air at the service unit is presumably equal to that of the surrounding area T_0 . The supply pressure is 8.8·10⁵Pa, so the amount of exergy within the total pneumatic energy at the compressed air supply of the machine is 62% (equation (3)).

For the description of the energy distribution after the service unit, the difference in exergy between two observation points (e.g. $1\rightarrow 2$) can be used /7/.

$$\Delta \boldsymbol{E}_{\text{ex},1\to2} = \boldsymbol{E}_{\text{ex},1} - \boldsymbol{E}_{\text{ex},2} = \int \dot{\boldsymbol{m}} \cdot \left(\boldsymbol{h}_1 - \boldsymbol{h}_2\right) - \dot{\boldsymbol{m}} \cdot \boldsymbol{T}_0 \cdot \left(\boldsymbol{c}_p \ln\left(\frac{\boldsymbol{T}_1}{\boldsymbol{T}_2}\right) - \boldsymbol{R} \ln\left(\frac{\boldsymbol{p}_1}{\boldsymbol{p}_2}\right)\right) \cdot \boldsymbol{dt}$$
(4)

For the calculation of the exergy difference the temperatures T_1 and T_2 have to be determined. Due to the high complexity of the system and the limited number of available measuring equipment the high dynamic measurement of the temperature is very demanding. Therefore the temperature of the compressed air at the different observation points is not measured but set equal to that of the surrounding area T_0 . The temperature should be included in the considerations for detailed studies.

If useful work passes the system boundaries between two observation points, a balancing according to the equations shown in Figure 3 have to be performed. The leakage of the system is determined during the standstill of the machine.

4. Energetic analysis of the automatic placement machine

4.1. Energy consumption during a machine cycle

For the experimental investigation of the machine the required measuring points are to be selected in accordance with the observation points seen in Figure 3. The energy consumption of the entire machine is determined by measuring the mass flow \dot{m}_{su} and the supply pressure p_{su} at the service unit. The energy consumption of the subsystems is determined using measurements of the mass flow \dot{m}_v at the valve terminals and the operating pressure p_1 . At the individual drives the emitted useful work W_t is quantified through the load force, the inertia force and the friction force. At the cylinder drives the friction force is calculated via the equilibrium of forces at the piston through a measuring of the chamber pressure and the piston stroke during the various motion phases. In order to ascertain the electrically consumed energy flow \dot{E}_{el} at the directional valves, a current and voltage measurement is conducted at the solenoids. Furthermore information about the operation processes at the machine must be recorded. Due to the highly number of operation processes it is sensible to record the control signals of the directional valves and the signals of the end stop switches. This can for example be achieved by extracting said information from the field bus protocol.

The machine can also be simulated and analysed using a simulation model with lumped parameters (*SimulationX*). The principal structure of the simulation model matches the structure of the machine in Figure 2. The parameterisation of the components requires a multitude of characteristics which can be obtained from data sheets, pneumatic circuit diagrams and measurement data. In case of very complex structures of the handling system simplified equivalent systems are used. The controlling of the simulation model is handled using a linked virtual PLC (Programmable Logic Controller).

Figure 4 shows the energy flow and energy consumption of the automatic placement machine determined via measurement and simulation. The amount of consumed energy of this handling system $E_{pn,cycle}$ is low during a machine cycle, the cause for this being the high number of small cylinders with short stroke and the low mass of the handling object (mass of the plug housings $18 \cdot 10^{-3}$ kg). The results of the experimental and simulation-based analysis of the total pneumatic energy consumption during a machine cycle are comparable. Thus it is possible to simulate the pneumatic handling system with sufficiently accurate system behaviour.



Figure 4: Energy flow and energy consumption of the automatic placement machine The consumed electric energy E_{el} of the solenoid valves during a machine cycle amounts to 175J. The consumed electric energy is relatively low compared to the consumed pneumatic energy.

4.2. Analysis of energy distribution and identification of energy saving potentials

The energy distribution within the machine is determined using equation (4) as well as the equations shown in Figure 3 and is based on the experimental and simulationbased results. Investigating using a simulation model offers the advantage of more observation points being able to be monitored, hence enabling a more detailed analysis of the various fractions of energy. **Figure 5** shows the results of energy distribution within a handling system determined via simulation. The schematic distinguishes the categories <Functions> and <Potentials>. The category <Functions> contains all those parts which are required for the realisation of the operating tasks at the actuators. Specifically in cylinder drives those parts required are acceleration of the mass, the implementation of the movement task with a certain speed profile and the controlling of the actuator. Every cylinder drive is assigned a certain fraction of energy marking the drives with the highest energy consumption. The category <Potentials> contains those parts which not necessarily required for fulfilling the operating tasks.



Figure 5: Simulation-based investigation of the energy distribution

At the automatic placement machine, a reduction of the pressure level from the supply pressure to the operating pressure is performed, causing a high entropy production. The decrease in pressure at the service unit can be reduced, however a change in operating pressure has a significant impact on all drives of the machine.

The machine's drive systems are designed with generous tube lengths. The tubing must be filled at every double stroke of an actor. The energy stored within is subsequently vented in the form of exhaust air. The length of the tubing should be kept as short as possible to minimize the required compression energy at the actuators. Recycling the exhaust air presents an important energy saving potential. Throttling the exhaust air leads to high losses in pressure, the use of pneumatic circuit concepts with an alternative speed control system for the actuator therefore presents another very promising energy saving potential.

5. Selection and implementation of energy saving measures

As evidenced in the state of research chapter, a multitude of possible energy saving measures are presently known. **Figure 6** displays potential energy saving measures for pneumatic handling systems.



• Long tubing

Use of an exhaust air recovery circuit

Many cylinder drives

Energy saving potentials

	37			г -		
•	Ex	hau	ısta	ir re	ecov	ery

Alternative speed control for cylinder drives

eference XENON with small dimensions cylinder drives					
Criteria Energy saving methods	Effort	No influence on the dynamic of the drives	Saving potential	$\frac{\text{Benchmark}}{\sum (\text{Weighting} \cdot \text{Value})}$	
Weighting	2	1	3		
Parameter optimization (Dimensioning, adaptation of the working pressure)	4	3	4	23	
Improvement of components (Reducing leakage, reducing pressure losses)	1	5	3	16	
System modification (Decentralized valve arrangement, different pressure levels)	2	3	5	22	
Alternative pneumatic circuits (Exhaust air recovery circuit)	4	2	4	22	
Modification of the control strategy and valve technology (Multi-switching or servo pneumatic valve, Several directional valves)	1	4	5 5 Very	21 good	
Parameter optimiza	ition	s	Selection of energy saving method for the implementation at cylind		

for the implementation at cylinder drives with high energy consumption

Figure 6: Selection of suitable energy-saving measures

In Figure 6 these energy saving measures are compared based on a variety of criteria. A ranking of said criteria is presented based on the attributes and the detected energy saving potentials of the automatic placement machine. As first energy saving measure the parameter optimization is selected, meaning a mathematical optimization of the design parameters of the drive structure. The objective of the optimization is the reduction of the energy consumption of the drive while sustaining the motion profile. As a second energy saving measure the implementation of an exhaust-air recovery system is suggested which adds a storage circuit to the original configuration of the drive. This makes the utilization of the exhaust air of a piston chamber for the backward stroke possible and eliminates the need for a metering throttle. Both energy saving measures are implemented at the exhaust-air-flow-controlled cylinder drives with the highest energy consumption.

In the following the implementation of the mentioned energy saving measures is presented using an example drive system. This drive system is a standard exhaust-air-

flow-controlled cylinder drive of the machine. The drive is designed as a double piston cylinder with an oil brake. At first the modification is tested with the help of a simulation model and subsequently validated using experimental methods. The performed parameter optimization has conclusively shown that the operating pressure must be lowered using a pressure regulator, that tubing must be shortened and the metering throttles must be opened. This is followed by the installation of an exhaust-air recovery system, by means of installing two additional directional valves as well as a compressed-air reservoir. The appropriate operating parameters like volume and initial pressure of the storage can be determined via simulation. Figure 7 compares the system behaviour of the drive as well as the energy flow and energy consumption before and after the modification using experimental means.



Figure 7: Experimental validation of the energy savings using an exhaust-air recovery system and a parameter optimization for a standard cylinder drive

After the modification the motion profile reads a delay Δx_v in the backward stroke of the cylinder. This does not pose a restriction as far as the functionality of the drive within the machine is concerned since the backward stroke is not time-sensitive. The modified drive structure results in energy savings amounting to 55.8%.

In the order displayed in Figure 5 another five cylinder drives with high energy consumption are improved using the two energy saving measures and the total energy saving amount achieved for the entire machine is determined. The experimentally determined power and energy consumption of the automatic placement machine after

the modification is presented in **Figure 8**. Compared to the original configuration the automatic placement machine requires 23% less energy after one machine cycle.



Figure 8: Experimental validation of the total energy savings after modification of six selected cylinder drives

The experimental validation of the energy saving has proved that the advanced machine configuration – previously determined in the simulation model – can actually be implemented in the real machine. The installation of additional components for the implementation of the exhaust-air recovery system resulted in additional costs. Based on the reduced costs made possible by the saved energy in the automatic placement machine, an amortisation of the installation cost is achieved after a two years period.

Under the assumption of an energy saving potential of 55% per drive (see Figure 7), the total energy saving in case of the modification of all cylinder drives can be estimated up to 34%.

6. Conclusion

This article shows the basics for a systematic improvement of the energy efficiency of standard pneumatic handling systems. Thus far such systems were not designed with respect to energetic issues but to functionality. The proposed approach is practical and is demonstrated using a representative handling system.

For the energetic improvement of the system an experimental and simulation-based analysis is conducted with focus on the energy distribution aiming at the identification of components with high energy consumption and of possible energy saving potentials. The analysis of the automatic placement machine has successfully proven, that a significant energy saving potential lies in the utilization of the exhaust-air of the cylinder drives. This potential is even greater when an exhaust-air flow control is not used for the purpose of speed control.

This paper shows several different measures for saving energy at pneumatic handling systems. Based on the identified energy saving potentials two suitable energy saving measures are selected and implemented at six cylinder drives with high energy consumption. Exhaust-air recovery systems as well as an optimization of the operating parameters are used in this process.

The use of the energy saving measures is initially tested in a simulation model and subsequently the machine is modified for validation purposes. As a result a total amount of saved energy of 23% could be proven as compared to the standard configuration.

Pursuing studies should focus on the influence of the temperature on the energy distribution within pneumatic handling systems and specifically on developing methods for the early inclusion of energy saving measures in the construction process.

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9. Nomenclature

Ε	energy	J	С	flow velocity	m/s
E _{ex}	exergy	J	Cv	isochoric specific heat capacity	J/(kg·K)
Ė	energy flow	W	g	gravity	m/s ²
Н	enthalpy	J	т	mass	kg
H_0	enthalpy (ambience)	J	'n	mass flow	kg/s
Q	heat	J	p 1	operating pressure	Ра
Ż	heat flow	W	\pmb{p}_{su}	supply pressure	Ра
S	entropy	J/K	t	time	S
Т	temperature	К	x	displacement	m
T ₀	ambient temperature	К	Ż	velocity	m/s
U	internal energy	J	Ζ	geodetic height	m
W_{t}	mechanical work	J	PC	piston chamber	