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# Waste heat recovery from the air preparation room in a paint shop

**ANDRZEJ ADAMKIEWICZ**[a]
**PIOTR NIKOŃCZUK**[b*]

[a] Maritime University of Szczecin, Faculty of Maritime Engineering, Wały Chrobrego 1-2, 70-500 Szczecin, Poland

[b] West Pomeranian University of Technology, Szczecin, Faculty of Maritime Technology and Transport, Piastów 41, 71-065 Szczecin, Poland

**Abstract** The policy of sustainable development seeks to improve energy efficiency of industrial equipment. Efforts to improve energy efficiency also apply to the paint shops, where the recovery of waste heat is sought. The main source of a large amount of low-temperature waste heat in the paint shop is the spray booth. The second place where a large amount of low temperature waste heat is released is the room where the compressed air is prepared. Low energy efficiency of air compressors requires a large electric power supply. As a result, the emitted large heat fluxes become waste energy of the technological process. Heat is equivalent to up to 93% of the electric power supplied in the air compression process. There are solutions for recovering heat from compressors coming from the oil cooling water, but then the waste heat from the cooling of the compressed air and from the electric motor is released into air in the room. A method for recovering low-temperature waste heat from the air preparation room by means of an air-source heat pump has been proposed. An energy balance of the air compression and dehumidification process for the paint shop was made. A Matlab's built-in numerical model includes air compressor and dehumidifier, heat recovery and accumulation for the purposes of use in the spray booth. A simulation experiment was carried out on the effectiveness of heat recovery from the air preparation room. The use of combined energy management in paint shops was proposed.

**Keywords:** Waste heat recovery; Air compression; Paint shop

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[*] Corresponding Author. Email: piotr.nikonczuk@zut.edu.pl

# 1 Introduction

The policy of sustainable development seeks to improve energy efficiency of industrial equipment. A lot of analyses have been carried out for waste heat recovery technologies [8]. They were conducted in aspects of technical possibilities [7,9,10], economic [2,3,5], geographic position and optimization of heat recovery [21]. Efforts to improve energy efficiency also apply to the automotive industry, where heat recovery in paint shops and improvement of energy efficiency in other production processes are sought [6]. For paint booths, solutions for heat recovery have been developed [16,17], analyses [18] have been carried out, including the impact of overspray sediments on the decrease of heat recovery efficiency [14,15]. The paint shop also uses compressed air, where during its preparation low-temperature waste heat is generated. For installations with low-temperature waste heat, there are several solutions [7,8] also developed for the automotive industry [4]. Low energy efficiency of air compressors requires high electric power supply. As a result of air compression, large waste heat flux of low temperature is emitted by the compressor into the room in which it was installed. The waste heat constitutes up to 93% of the power supplied to the air compressor [1]. Three heat sources are released in the process of air compression: oil cooling, cooling of the compressed air and the electric motor [1]. There are solutions for recovering heat from compressors coming from the oil cooling water, but then the waste heat from the cooling of the compressed air and from the electric motor is released into the air in the room. Many solutions for low temperature heat recovery with the use of recuperators [24] as well as organic Rankine cycle (ORC) technology have been developed [9], including heat recovery methods from compressor oil [12]. For painting processes, it is also necessary to ensure proper parameters of the compressed air, including its humidity. That is why refrigeration air dryers equipped with a low-power heat pump are used in the installation of the compressed air preparation. The power of the waste heat flux emitted from the refrigeration dryer is several times higher than the electric power consumed. This phenomenon is related to the energy efficiency ratio, coefficient of performance (COP), of heat pumps and the recovered heat from the compressed air. On average, it can be assumed that COP = 3. The possibilities of heat recovery from the process of compressed air drying were considered [5]. Figure 1 presents a qualitative band diagram of the electric and thermal power balance in the process of preparing compressed air using a compressor and refrigeration dryer. The electric power of the compressor and the dryer was separated. For the compressor, the electric power used for air compression were separated from its waste heat. Power of the waste heat flux from the dehumidifier is three times higher than its consumed electric power.

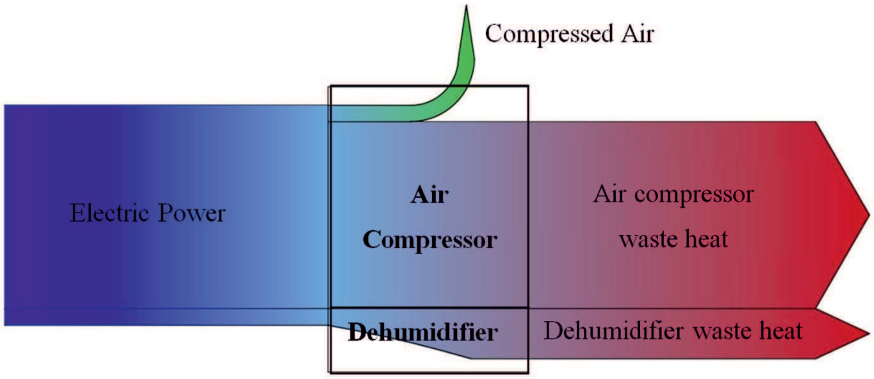

Figure 1: A band graph of the energy balance of air compression and drying processes.

In the process of compression and air drying, the total power of the waste heat flux is greater than the electric power supplied in the process of air compression [1,26]. This is the basis for applying solutions of heat recovery systems. Current systems use solutions which are suitable for recovering heat from the high power compressors equipped with the oil water cooling systems. The heat is recovered from the water circuit, without the waste heat from air cooling and electric motors of the compressors. Similarly, in the case of high power dehumidifiers, the waste heat is recovered from the water cooling system [1,3,5,12], without the heat from the refrigeration compressor motor.

Low power air preparation installations are equipped with an air-cooled compressor and an air-cooled refrigerant dryer. The authors proposed the of low-temperature waste heat recovery using an air-source heat pump.

## 2 Mathematical model of heat exchange in a paint shop

In order to analyze the efficiency of heat recovery using an air-source heat pump, a mathematical model of the air preparation room was constructed on the example of a paint shop. Figure 2 shows a simplified diagram of the compressed air preparation room. The room contains the air compressor, refrigeration dryer, compressed air tank and an air-source heat pump with the hot utility water tank constituting a heat accumulator.

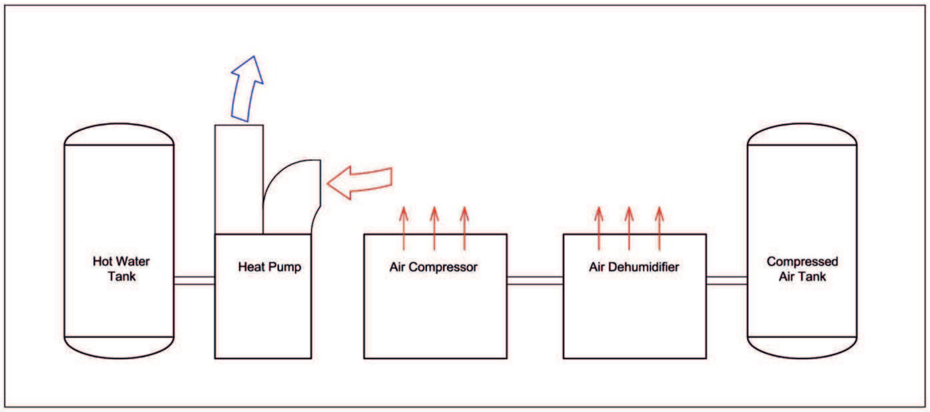

Figure 2: A simplified diagram of the air preparation room with recovery of waste heat.

The compressor and the refrigerant dryer transfer heat to the room. The air heat pump recovers heat from the room and transfers it to the heat accumulator, which is a water tank. The waste heat flux given off by the compressor, $dQ_c/dt$, is described by the following equation:

$$\frac{dQ_c}{dt} = k_c P_c \,, \tag{1}$$

where: $k_c$ – coefficient of the heat released by the compressor, $P_c$ – electric power, $t$ – time.

The waste heat flux, $dQ_d/dt$, dissipated from the refrigerant dryer is a function of the energy efficiency coefficient of the heat pump, $\mathrm{COP}_d$, and its electric power, $P_d$,

$$\frac{dQ_d}{dt} = \mathrm{COP}_d \; P_d \,. \tag{2}$$

The temperature change of the room air, $\Delta T_a$, is determined from the following equation using the balance of heat fluxes exchanged in the compressed air preparation room with a compressor and an air-cooled refrigerant dryer

$$\Delta T_a = \frac{(Q_c + Q_d - Q_{hp})c_a}{V_a \rho_a}\,, \tag{3}$$

where: $Q_{hp}$ – heat taken from indoor air by the heat pump, $Q_c$ – heat given off by the compressor, $Q_d$ – heat given off by the refrigeration dryer, $c_a$– specific heat of the air, $\rho_a$– air density, $V_a$ – volume of the room.

The air inside the room is parameterized by its specific heat, $c_a$, density, $\rho$, and room volume, $V_a$. The change in the water temperature, $\Delta T_w$, is determined by the heat flux delivered to the water tank, $Q_{hp}$, by the heat pump and water parameters: specific heat, $c_w$, density, $\rho_w$, and the volume of the water tank, $V_w$,

$$\triangle T_w = \frac{Q_{hp} c_w}{V_w \rho_w}\quad . \tag{4}$$

The instantaneous electric power required by the heat pump is related to the function of the instantaneous efficiency coefficient, $\mathrm{COP}_{hp}$, and the heat flux power transferred by the heat pump to the water tank

$$P_{hp} \quad = \frac{\dfrac{dQ_{hp}}{dt}}{\mathrm{COP}_{hp}}\quad . \tag{5}$$

The instantaneous energy efficiency value of the air heat pump depends on the temperature of the upper and lower heat sources. For the modeling of instantaneous changes of the coefficient of performance value, a generalized description of the changes in the form of the exponential function [25]

$$\mathrm{COP}_{hp} = 49.3(T_r - \; T_a)^{-0.777} \tag{6}$$

has been adopted, where $T_r$ is the temperature of the refrigerant in the heat exchanger in the water tank acting as a condenser and $T_a$ is the temperature of the room air.

# 3 Simulation studies

## 3.1 Simulation model

Using the presented mathematical description, a room simulation model was created in the Matlab/Simulink commercial software packages: Matlab environment (a high-level language and interactive environment for numerical computation, visualization, and programming) [27] and Simulink (a graphical programming environment for modeling, simulating and analyzing) [28]. The model has four components: a compressor with refrigeration dryer and a tank of compressed air; an air preparation room; a heat pump and a tank with warm water. The schematic diagram of the paint shop's block model is shown in Fig. 3.

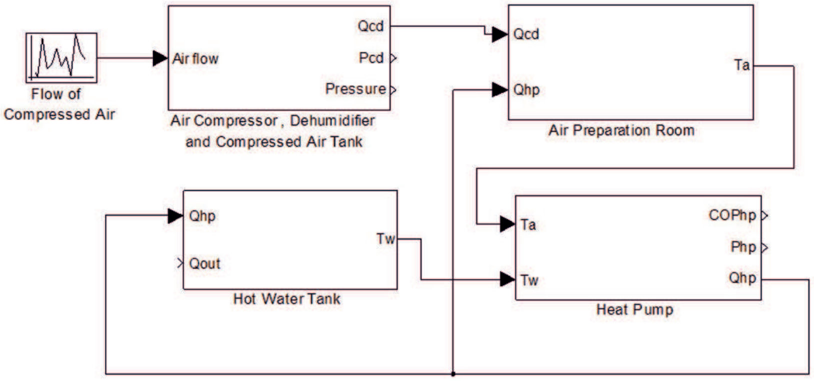

Figure 3: A block diagram of the simulation model in the Matlab/Simulink software.

In the block of the compressor together with the dryer and the tank, $Q_{cd}$ denotes the total waste heat transferred by the compressor and the dryer to the air in the *air preparation room*. Heat, $Q_{hp}$, taken from the air in the room by the heat pump and transferred to the water tank is also an input parameter of the *air preparation room* block. Water temperature, $T_w$, is an output parameter of the *hot water tank*. Air temperature in the room, $T_a$, is an input for *heat pump* block, it is used to calculate the instantaneous values of the energy efficiency coefficient, $\text{COP}_{hp}$, of the heat pump and the instantaneous electric power, $P_{hp}$, consumed by the heat pump. It was assumed that in the room the air is not exchanged and there is no heat exchange between the air and the surroundings outside the room.

As a modeling and simulation object, parameters of a set comprising a compressor and its dedicated refrigerated dryer, offered on the commercial market were adopted [26]. Basic technical data of the adopted set are presented in Tab. 1. The heat flux emitted by the air compressor was determined according to Eq. (1), the value of coefficient of heat released by the compressor was assumed $k_c = 0.93$. The heat flux derived from the dehumidifier was determined according to Eq. (2), the value of energy efficiency coefficient of the heat pump $\text{COP}_d = 3$ was assumed.

Table 1: Basic parameters of items used in the model [26].

| | Compressor | Refrigerated dryer |
|---|---|---|
| Model | SC-10 | AD-10 |
| Performance at 800 kPa | 0.02 $m^3/s$ | up to 0.025 $m^3/s$ |
| Cooling | air-cooled | air-cooled |
| Electric Power | 7.5 kW | 0.62 kW |

The parameters of the modeling components used in the simulations were: a compressed air tank with a capacity of $V_a = 0.3$ m$^3$ (300 L) and pressure of 800 kPa, as a receiver of coupled air one spray gun with a nominal air intake of 0.0072 m$^3$/s (430 L/min) and a pressure of 250 kPa was taken. The spray gun always takes the nominal air volume during operation, however, the step time in the simulation is longer than the possible times of launching the spray gun. Therefore, the work of the spray gun was simulated in a simplified way by instantaneous variable random values not exceeding the nominal air intake of the gun. The maximum heat output of the heat pump $dQ_{hp}/dt = 6$ kW and the capacity of the water tank $V_w = 0.3$ m$^3$ was assumed. The volume of the compressed air preparation room was assumed $V_a = 64$ m$^3$.

## 4 Simulation results

For the above parameters, one hour of model operation was simulated. Figure 4 shows the runs of changes of waste heat flux emitted into the room through the compressor and a compressed air dryer. For comparison, the total power consumption of the compressor and dryer is also presented. The phenomenon of higher thermal power emitted by the system than the consumed electric power described in the introduction is clearly noticeable. Co-ordinate system 4c shows the heat flux drawn from the air by the heat pump and transferred to the water tank. Figure 4d shows the electric power consumed by the heat pump. All values in the charts are the result of the work of one spray gun.

Figure 5 shows the runs of changes in the compressed air flow drawn by the spray gun from the compressed air tank (5a) and changes of pressure inside the air tank (5b). The pressure in the compressed air tank is filled

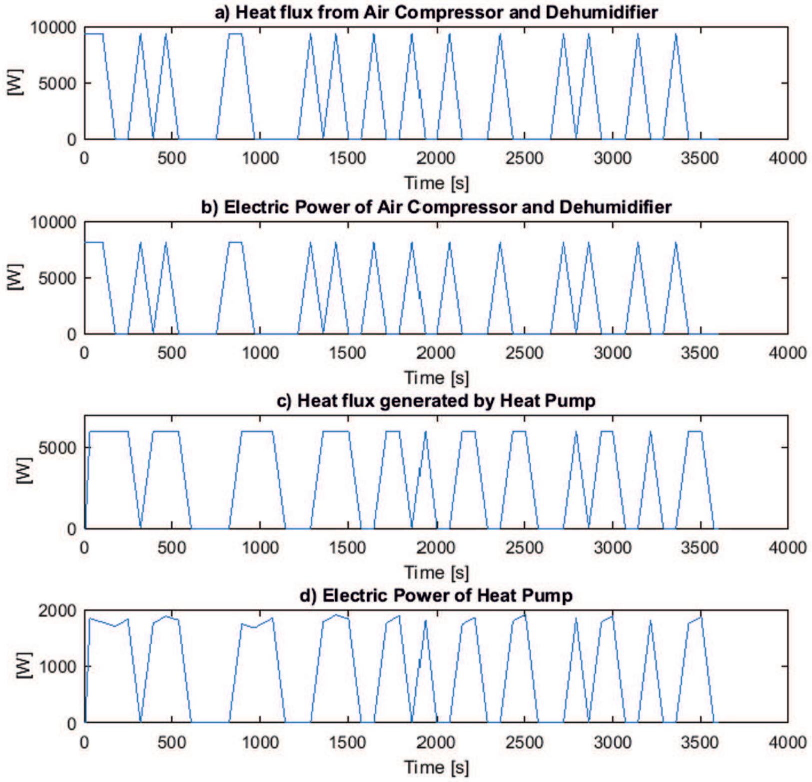

Figure 4: Heat flux and power consumption of the compressor, dryer and heat pump.

by the compressor via the air dryer. The compressor and the dryer emit waste heat and heat the room. An air source heat pump extracts heat from the room and accumulates it in the heat accumulator (a water tank). Changes in the air temperature inside the room (5c) and changes of the water temperature in the tank (5d) were also presented.

Changes in the waste heat exchange parameters are presented in Fig. 6. Figure 6a shows change patterns of the heat emitted by compressor with the dryer and the heat drawn from the air by the heat pump. For comparison, the electric power consumed by the heat pump (6b) is shown as well. Changes of the heat pump energy efficiency ratio COP exceeding the value of 3 are also presented in Fig. 6c.

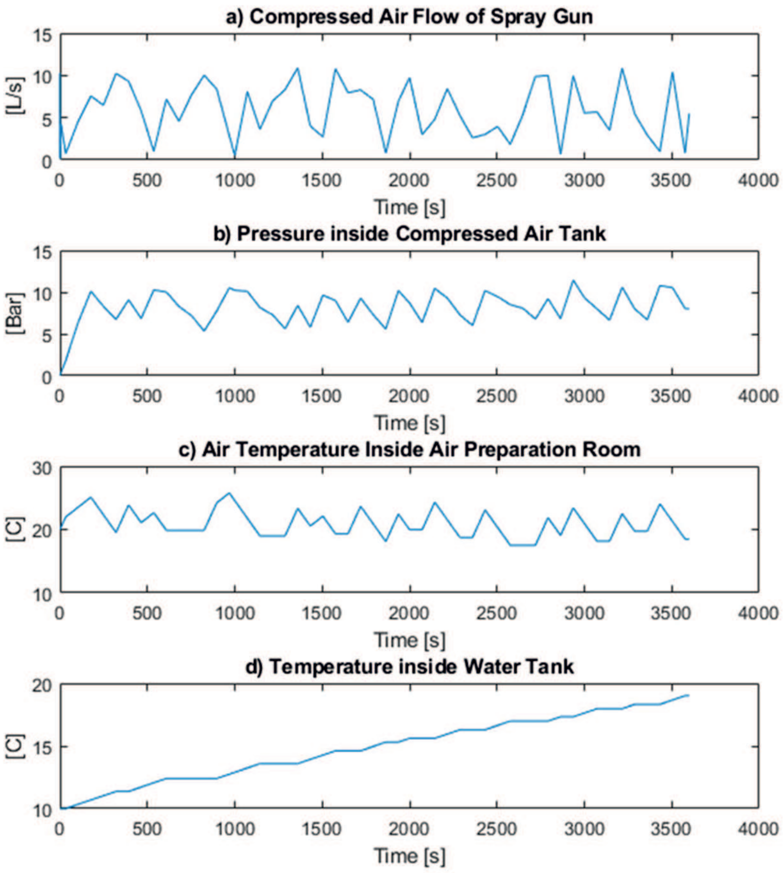

Figure 5: Air drawn by the spray gun (a), pressure inside the compressed air tank (b), temperature changes inside room (c), and the water tank (d).

## 5 Summary, conclusions and recommendations

The obtained results justify the need to recover waste heat from the compressed air preparation plant. In the simulation, as a result of compressed air supply for one spray gun within one hour the temperature of the water in the 0.3 $m^3$ tank increased by almost 20 °C. Electric power consumption is more than three times smaller than the recovered thermal power. Air source heat pumps offered on the market achieve COP above 4. When designing a heat recovery system, thermal balance of the paint shop is re-

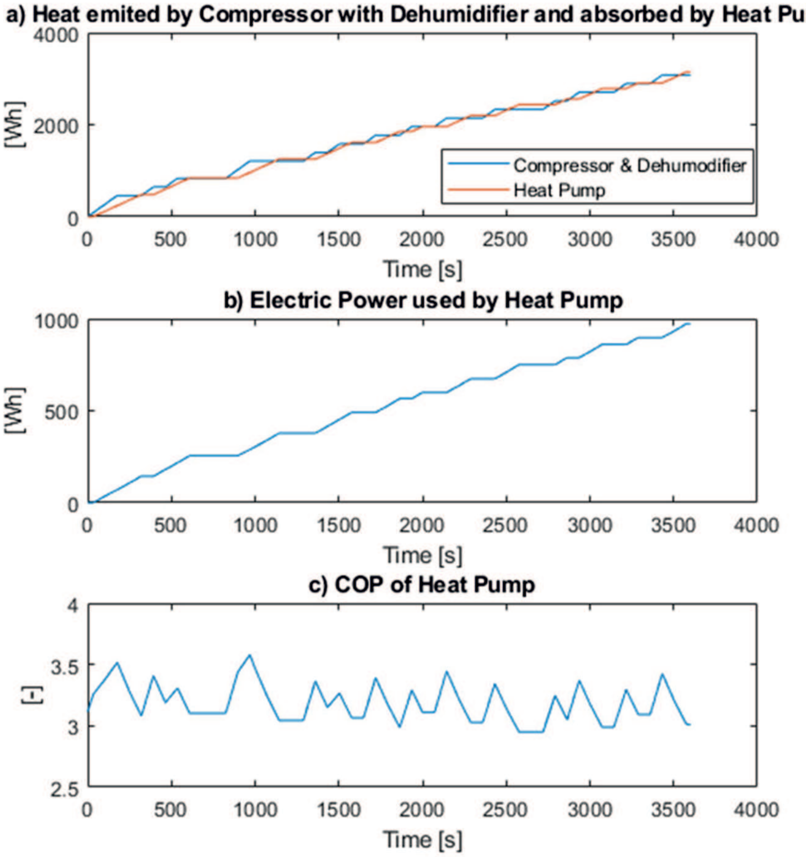

Figure 6: The heat emitted to the room and drawn by the heat pump (a), electric power drawn by the heat pump (b) and the COP of the heat pump (c).

quired, which includes waste heat and daily heat demand. Based on the results of the balance, it is possible to select a heat pump with the appropriate thermal power and the capacity of water tank constituting a heat accumulator.

The obtained runs of parameters reflect the simulation of the work of the paint shop during one hour. They represent the costs of electric energy used to air supply for one spray gun operation. Heat recovery in simulations was estimated on the basis of heat pump COP described by simplified function [25]. Determining the heat flux for the real system requires knowledge of the heat pump parameters. Knowledge of these parameters enables optimization of paint shop operation or construction [13].The real paint shop also works with other tools powered by compressed air, for example, pneumatic powered grinders. In addition to the large energy expenditure, working with pneumatic tools involves a lot of low-temperature waste heat. The use of comprehensive energy management in compressed air systems is justified [1,11], as well as a correct management of compressed air [3,22,23].

The presented method with the use of an air-source heat pump enables the recovery of heat from all the devices of the compressor and the dryer and storing it at the water tank. The heat accumulated at the water tank can be used for other purposes, for example to air heating in the spray booth. The technology for heat exchange between the paint booth and other installations was developed [16] and a preliminary analysis was accomplished for it [18]. It is the basis for the development of energy combined paint shop. The proposed waste heat recovery technology is presented on the case of a paint shop, however, compressed air is used in many industrial processes with a much larger volume of air, where more waste heat is also released. The main advantage of this method is the lack of the need to interfere in the compressed air preparation system and it is limited to place in the room, a heat exchanger or an entire air-source heat pump.

The rational optimization of the heat pump's operation should minimize the consumption of electric power by obtaining high COP values; it is possible with individual consideration of each installation.

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