Utilization of Waste Heat from Industrial Air-Cooled Compressors

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Abstract: *Industrial compressed air systems are generally considered inefficient, with end users consuming only 10% to 30% of primary energy. Therefore, the inefficiencies of these systems must be minimized. By improving compressed air components and systems and using them correctly, you can save 20% to 50% on electricity, reduce costs, reduce downtime and increase productivity. A relatively large number of measures and activities can be implemented to reduce energy consumption in compressed air systems. The purpose of the work is to present the process of analyzing the use of waste heat from an air-cooled compressor for space heating in an industrial company. The method is applied to a case study of an industrial company in the food industry. The utilized waste heat presents 36.6% of the total electricity consumed by compressors in the facility. This energy efficiency measure saves more than 3% of the total heat consumed in the company while the payback period is less than 7 months.*

Keywords: *compressed air, industrial compressors, heat recovery, energy efficiency, energy savings*

Article Classification: *Scientific paper*

1 INTRODUCTION

Compressed air has a very wide application in industry. Many production plants, from small craft workshops to large industrial plants, use compressed air in two ways: as an energy transfer medium and as a part of the process when the air comes into contact with the product. Compressed air is widely used in industries such as general manufacturing, automotive, food and beverage, plastics, chemicals, pharmaceuticals, semiconductors and electronics, agriculture and farming, and construction [1].

Compressor operation requires a substantial quantity of electrical energy, and compressed air energy expenses account for a significant portion of total energy costs in the majority of industrial companies [2]. Industrial compressed air systems are generally considered inefficient, with end users consuming only 10% to 30% of primary energy [3]. Therefore, the inefficiencies of these systems must be minimized. By improving compressed air components and systems and using them correctly, one can save 20% to 50% on electricity, reduce costs, reduce downtime, and increase productivity [4]. A relatively large number of measures and activities can be implemented to reduce electricity consumption in compressed air systems [2, 5, 6, 7].

Besides, additional savings in heat energy consumption in industrial facilities can be achieved by using the waste heat generated in the compressor cooling process. Using cooling fluids (water [8] or air [9]) in a well-designed and constructed heat regeneration system, an industrial facility can utilize up to 50% to 90% of this waste heat for various purposes [10]. It is estimated that about 15 kW of thermal energy is available for every 500 l/s of compressor capacity (at full load) [11]. The most cost-effective technique to recover the heat is to use it for space heating. It requires an air-cooled compressor through which the cooling air is introduced and heated. This heat recovery method is cost-effective since it recovers all heat, including radiated heat in the compressor. The heated cooling air must be routed through a duct system to the consuming area. In most factory environments, the noise produced by compressors and any reduction in the freshness of the recovered air typically go unnoticed. However, in more sensitive working areas, such as IT assembly zones, it may be necessary to consider sound attenuation and air filtering measures [12]. This type of heat recovery can only be employed during the heating season. In the non-heating season, the waste heat is discharged to the outside environment. In general, the payback periods of using waste heat recovery for space heating in various industrial companies are usually very short (often less than one year [13]).

Considering the above, this paper considers the utilization of waste heat from air-cooled compressors for heating purposes in an industrial plant in Kragujevac, Serbia.

2 METHOD

The method applied in the paper is presented in Figure 1.

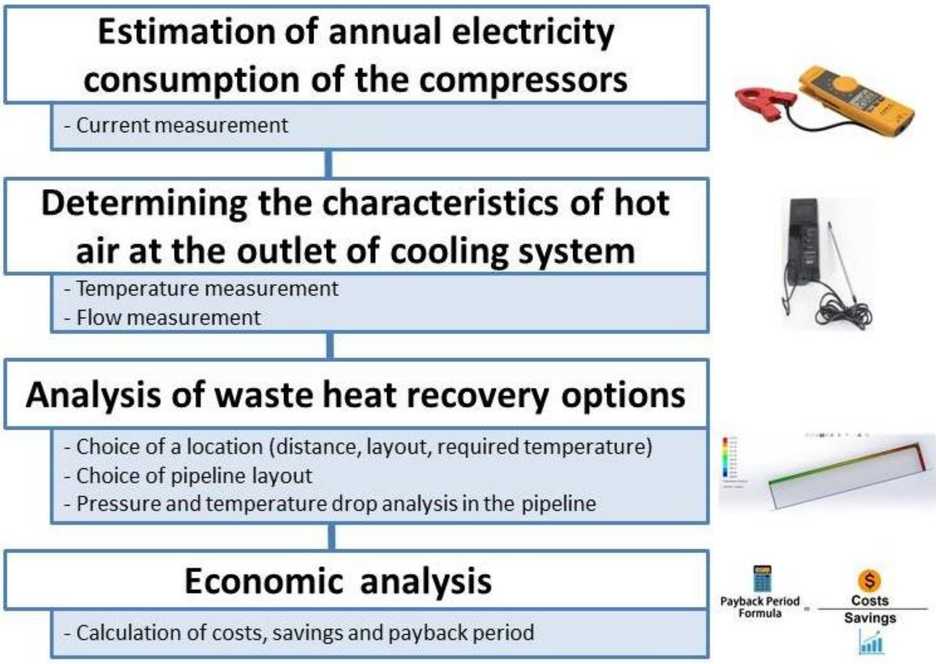

Figure 1: The method for estimating the potential of waste heat utilization from industrial air-cooled compressors

The first step considers estimating annual electricity consumption E [kWh] of a compressor using the following equation:

$$E = \sum_{i=1}^{n} I_i \cdot U \cdot \sqrt{3} \cdot \cos\varphi_i \cdot \tau_i \cdot 10^{-3} \tag{1}$$

Where:

n [-] - number of working regimes of a compressor,
I_i [A] - air compressor motor current (average measured value for all three phases) in the *i*-th operating mode of the compressor,
U [V] - three-phase voltage (400 V adopted value),
$\cos\varphi_i$ [-] - power factor at the *i*-th operating mode of a compressor,
τ_i [h] - estimated annual engagement of a compressor in the *i*-th operating mode.

Detachable Jaw True RMS AC/DC Clamp Meter Fluke 365 was used to measure the current (Figure 2). The Fluke 365 is a robust handheld meter with detachable clamps, intended for measurements in facilities with difficult access. Current (AC and DC), voltage (AC and DC) and resistance can be measured with this device.

<u>Technical specification (current):</u>

Range AC - DC	200 A
Resolution AC - DC	0,1 A
Accuracy	±2 %

Figure 2: Clamp Meter Fluke 365

The nominal value of the power factor is adopted based on the manufacturer's data shown on the nameplate of the electric motor of the compressor. If the compressor load significantly deviates from the rated, the power factor change is determined using the diagram typical for 3-phase induction motor shown in Figure 3.

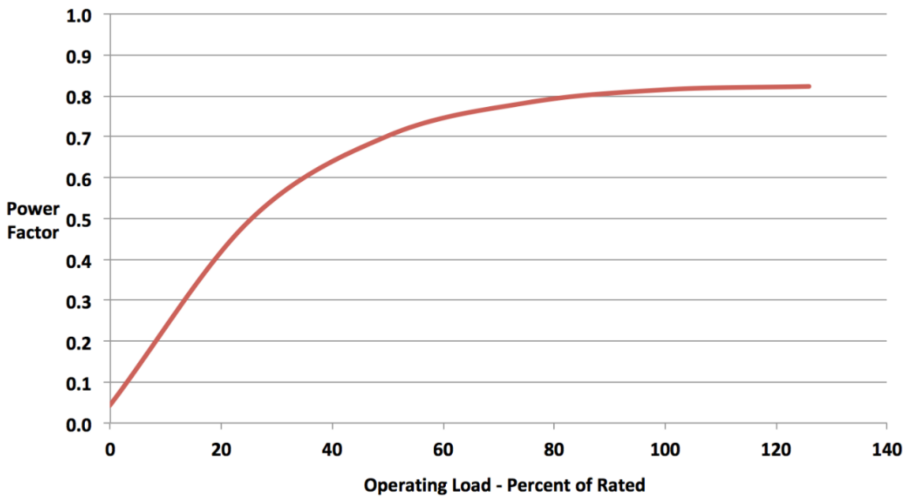

Figure 3: Variation of electric motor power factor with load change

The second step is to determine the thermodynamic properties of hot air at the outlet of the cooling system, which involves measuring the air temperature and flow rate. The measurements were performed using an ALNOR CompuFlow 8525 thermal anemometer, Figure 4. ALNOR CompuFlow 8525, enables the measurement of air speed and temperature at several points in the ducts. Using measured air speed data in several points of the cross section of the outlet cooling channel and knowing the geometry of the canal, the volumetric flow rate is calculated.

<u>Technical specification:</u>

Temperature range	0-70 °C
Resolution	0,1 °C
Accuracy	±0,3 °C
Air speed range	0,1-10 m/s
Resolution	0,05 m/s
Accuracy	±2,5%

Figure 4: ALNOR CompuFlow 8525 Thermal Anemometer

The analysis of waste heat recovery options first assumes the identification of a location where waste heat can be utilized. The required temperature and heating period are specified for the location. The distance from the outlet to the recovery location and the layout constraints are also determined. These parameters are necessary for designing the duct layout considering the shortest and most efficient path. Finally, the SOLIDWORKS Flow Simulation, a computational fluid dynamics (CFD) solution built into the SOLIDWORKS 3D CAD, is used to analyze the pressure and temperature drop in the duct line. A temperature analysis is necessary to determine the temperature of the air available at the location, while a pressure analysis should determine the necessity of installing an additional fan in the system.

The total amount of available waste heat WH [kWh] can be calculated from:

$$WH = \sum_{i=1}^{n} q_i \cdot \rho \cdot C_p \cdot (t_i - t_s) \cdot \tau_i \cdot \%\tau_i \cdot 10^{-5} \quad (2)$$

Where:
ρ [kg/m^3] - air density (adopted value 1,1 kg/m^3 for the temperature range 20-50 °C),
q_i [m^3/s] - volumetric flow of cooling the air in the *i*-th operating mode of a compressor,
C_p[J/kgK] - isobaric specific heat of air (adopted value 1000 J/kgK for the temperature range 20-50 °C),
t_i [°C] - air temperature at the duct outlet (heated room inlet) at the *i*-th operating mode of the compressor,
t_s [°C] - heated room temperature,
τ_i [h] - estimated annual engagement of a compressor in the *i*-th operating mode,
$\%\tau_i$ [%] - percentage of compressor working time when a heat recovery system can be used.

The final step is economic analysis, which includes calculating investment costs, estimating energy savings, and calculating a simple payback period.

3 RESULTS WITH DISCUSION

The proposed methodology was applied in a margarine processing company located in Kragujevac, Serbia. Compressed air is used in the company as an energy transfer medium for various pneumatic actuators, as well as to package the finished product. Two oil-injected Atlas Copco GA11 d1 rotary screw compressors are used. Both compressors operate in the load-unload mode. The waste heat generated during cooling is not utilized within the facility but instead is released outside through an opening in the outer wall of the compressor station (Figure 5).

Figure 5: The compressors at the production facility

To estimate the amount of electricity required for compressor operation, data on their annual time of engagement in full load and unloaded modes were taken from the control unit of the compressors. The currents were measured on several occasions and then the measured values were averaged. Using equation (1), the estimated annual electricity consumption of compressors is about 61.8 MWh (Table 1).

Table 1: Estimated annual electricity consumption of compressors

Compressor	1	2
Annual engagement - loaded [h]	1588	1518
Annual engagement - unloaded [h]	1121	1440
Total annual engagement [h]	2709	2958
Measured current - loaded [A]	22	
Measured current - unloaded [A]	15	
Nominal power factor (cosθ) [-]	0.85	
Power factor - loaded [-]	0.85	
Power factor - unloaded [-]	0.81	
Annual electricity consumption - loaded [kWh]	20,574	19,667
Annual electricity consumption - unloaded [kWh]	9,436	12,121
Total electricity consumption [MWh]	30.010	31.788
Total electricity consumption for both compressors [MWh]	**61.798**	

The cooling system of the compressors includes an axial fan. The average measured speed at the outlet cross section (0,6 m x 0,3 m) of the cooling system was 1,8 m/s regardless of the operation mode of compressors. Therefore, the volumetric flow of hot air was 0.324 m^3/s in both of the regimes. The cooling air temperature depended on the compressor operation mode. When the compressors were unloaded, it was 45 ˚C, but when they were loaded, it was 50 ˚C. Considering the air temperature in the compressor room (22 °C on average), the compressors consume about 85% of energy for cooling, which can be considered inefficient.

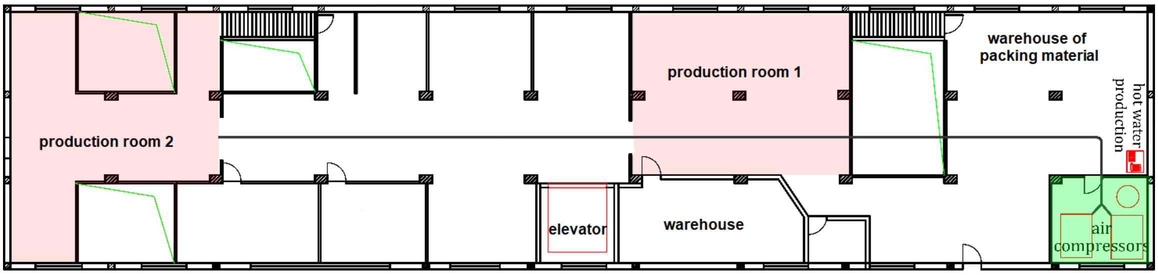

Figure 6: The position of the compressor room and possible locations of waste heat use

Two possible alternatives were analyzed for the selection of a location where waste heat can be utilized, production rooms 1 and 2 from Figure 6. The length of the duct is 15 m for room 1, i.e., 40 m for room 2. The ducts should be routed throughout the building, with the inside temperature of passing rooms estimated to be 18 °C. The results of pressure and temperature drop analyses in both cases performed in SOLIDWORKS Flow Simulation (Figure 7) were presented in Table 2. Although the ducts in both solutions were not routed outside the building, the performed simulation indicated an air temperature drop, especially in the case of room 2. The pressure drop analysis indicated that, in both scenarios, the total pressure drop—including the 5 Pa local pressure drop caused by the fully open damper—is below the maximum allowable pressure drop for the cooling air ducts (30 Pa [14]). Therefore, there is no need to include a fan at the outlet of the cooling air ducts in both cases.

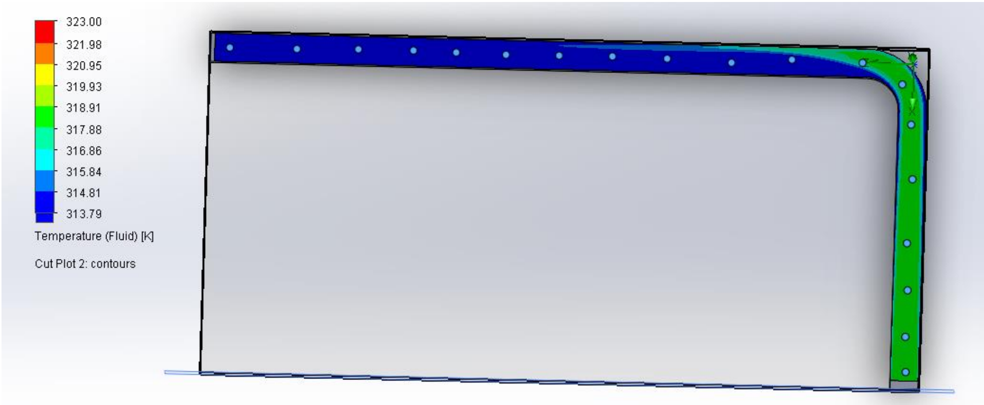

Figure 7: Temperature distribution in waste heat distribution duct (unloaded mode, 15 m duct)

Table 2: The results of pressure and temperature drop analysis

Production room	1		2	
Duct length [m]	15 m		40 m	
Compressors' working mode	Load	Unloaded	Load	Unloaded
Air temperature at duct outlet [°C]	44	39.8	35.9	33.5
Pressure drop in the duct [Pa]	2.2	2.2	4.2	4.2

Taking into account that both rooms should be heated to 20 °C and using equation 2, the total estimated annual waste heat potential for heating the room 1 is 47.1 MWh, and for heating the room 2 is 31,6 MWh. In the case of room 1, it presents about 76% of consumed electricity for compressing air, while for room 2, it is about 51%. Nevertheless, the heat recovery system can be used only during the heating season. Therefore, it was estimated that only at 48% of compressors' working time the heat recovery system can be used. This gives 22.6 MWh for the final total estimated annual waste heat potential for room 1 and 15.2 MWh for room 2. The three-year average total annual heat energy consumption for process and space heating in the factory is 725 MWh. The total savings of heat energy using waste heat from the compressors is 3.1% for heating the production room 1 and 2% in case of heating the production room 2.

With a heat (natural gas) price of 4,200 RSD/MWh and an exchange rate of 117 RSD/EUR, the total saving of 811 € will be in case of heating the production room 1, i.e., 544 € in case of heating the production room 2.

The estimated costs were 20 €/m for duct construction and 70 € for a gravity-operated damper, so in case 1, the total costs came to 440 €, or 940 € in case 2. There are no additional costs for adjustments or modifications of the factory heating system. This finally gives the payback period of 0.54 years (6.5 months) for the shorter duct and 1.73 years (20.7 months) for the longer duct.

4 CONCLUSION

The solution for using the waste heat from air-cooled compressors for space heating is relatively simple. The only needed modification in the system is the addition of ducting and associated dampers. The solution has a significant potential for increasing energy efficiency in the industry, even though it is used for a limited period of heating season.

The prerequisite for efficient application is the proximity of the space that is heated and the compressor. Increasing the duct length has a negative influence both on pressure and temperature drops of hot air. The case study reveals that in the case of a 15 m long duct line, which can be considered moderately long, the utilized waste heat accounts for 36.6% of the total electricity consumed by compressors. This energy efficiency measure saves more than 3% of the total heat consumed in the company, while the payback period of the energy efficiency measure is less than 7 months.

It should also be mentioned that a common issue with this heat recovery system is the absence of a clear indicator showing that heat is being recovered. Often, it remains in its winter setting throughout the year, leading to overheating during the summer. Similarly, it frequently releases heat when set to summer mode during the winter months. To prevent these problems, installing a clear indicator on the compressor control panel that displays the temperature of the recovered heat would be beneficial.

LITERATURE

[1] GIAMPAOLO, Tony. *Compressor Handbook: Principles and Practice*. Second Edition. Gistrup: River Publishers, 2023. ISBN 978-8770227377.
[2] SAIDUR, R., N.A RAHIM in M. A HASANUZZAMAN, A review on compressed-air energy use and energy savings. *Renewable and Sustainable Energy Reviews,* 2010, vol. 14, issue. 4, 1135-1153. DOI: https://doi.org/10.1016/j.rser.2009.11.013
[3] YEAPLE, Franklin D. *Fluid power design handbook*. 3rd Edition. New York: Marcel Dekker, Inc, 1996. ISBN 978-0824795627.
[4] GORDIĆ, Dušan et al. Ušteda energije u industrijskim sistemima komprimovanog vazduha kroz saniranje curenja. *Energija, ekonomija, ekologija*. 2008, vol. 10, issue. 1-2, 174-177.
[5] MOUSAVI, Smaeil, Sami KARA in Bernard KORNFELD. Energy Efficiency of Compressed Air Systems. In: *Procedia CIRP* [online]. 2014, vol. 15, 313-318. DOI: https://doi.org/10.1016/j.procir.2014.06.026
[6] RADGEN, Peter in Edgar BLAUSTEIN. *Compressed Air Systems in the European Union Energy, Emissions, Savings Potential and Policy Actions.* Stuttgart: LOG_X Verlag GmbH, 2001. ISBN 3-932298-16-0
[7] ŠEŠLIJA, Dragan, Ivana IGNJATOVIĆ in Slobodan DUDIC. Increasing the Energy Efficiency in Compressed Air Systems [online]. IntechOpen, 2012. Available at: https://www.intechopen.com/chapters/40201
[8] BRONISZEWSKI, Mariusz in Sebastian WERLE, The study on the heat recovery from air compressors, E3S Web of Conferences 70, 03001 (2018) Available at: https://doi.org/10.1051/e3sconf/20187003001
[9] HERNÁNDEZ, Herrera et al. Energy savings in compressed air systems a case of study. V: *IOP Conference Series: Materials Science and Engineering* [online]. 2021, roč. 1154, č. 1, 012009. DOI: https://doi.org/10.1088/1757-899x/1154/1/012009
[10] BEALS, Chris et al. Improving Compressed Air System Performance – A Sourcebook for Industry U.S. Department of Energy, Washington D.C., 2004. [13.09.2024]. Available at: https://www.energy.gov/eere/amo/articles/improving-compressed-air-system-performance-sourcebook-industry
[11] GORDIĆ, Dušan. Energy and Environmental Management in the Furniture Industry. Kragujevac: Faculty of Engineering, University of Kragujevac, 2011. ISBN 978-86-86663-77-1
[12] THUMANN, Albert in Scott DUNNING. *Plant Engineers and Managers Guide to Energy Conservation.* 10th Edition. Lilburn: Fairmont Press, 2011. ISBN 978-1-4398-5606-2
[13] Good Practice Guide 238: Heat recovery from air compressors [15.09.2024]. Available at: https://controlgear.net/documents/good_practice_guide_238_heat_recovery_from_air_compressors_1396339838.pdf
[14] Atlas Copco Oil-injected rotary screw compressors GA 11+, GA 15+, GA 18+, GA 22+, GA 26+, GA 30 Instruction book [13.09.2024]. Available at: https://www.aircompressorsdirect.com/manuals/atlasga30manual_2.pdf

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Organizatorji konference | Conference Organizers:
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Založnik zbornika | Publisher of Proceedings:
Fakulteta za industrijski inženiring Novo mesto | Faculty of industrial engineering Novo mesto
Kraj | Place: Šegova ulica 112, 8000 Novo mesto, Slovenija

Leto izida | Year: 2024

Tehnični urednik | Technical Editor: Matic Medvešek, dipl. inž. str.

Tisk na zahtevo.

CIP - Kat176ložni zapis o publikaciji
Narodna in univerzitetna knjižnica, Ljubljana

62-027.31:502.131.1(082)

MEDNARODNA konferenca o razvoju industrijskega inženiringa (9 ; 2024 ; Novo mesto)
Priložnosti, potenciali in izzivi za zeleni prehod = Opportunities, potentials and challenges for the green transition : zbornik recenziranih prispevkov 9. mednarodne konference o razvoju industrijskega inženiringa = proceedings of reviewed papers of the 9th International Conference on the Development of Industrial Engineering : Novo mesto, 21. november 2024 / [organizatorji konference Fakulteta za industrijski inženiring Novo mesto [in] Fakulteta za organizacijske študije Novo mesto [in] Rudolfovo - Znanstveno in tehnološko središče Novo mesto ; uredniški odbor Iris Fink Grubačević ... et al.]. - Novo mesto : Fakulteta za industrijski inženiring = Faculty of Industrial Engineering, 2024

ISBN 978-961-7097-14-6
COBISS.SI-ID 215372035

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