Engineering and Technology Journal e-ISSN: 2456-3358

Volume 08 Issue 03 March-2023, Page No.-2083-2089

DOI: 10.47191/etj/v8i3.13, I.F. – 7.136

Optimization of Vacuum System Energy Consumption in an Industrial Environment

Cheikh OBASEN JO

ABSTRACT: Greenhouse emissions are increasing, and the future of the earth and humanity is at stake. Many governments in the world have committed to reduce carbon emissions. At the United Nations Climate Change Conference (COP21) in Paris, France, an agreement has been reached to hold the increase in the global average temperature to well below 2°C above pre-industrial levels. Vacuum systems are very present in industry (agrifood, pharmaceuticals, chemicals) and energy consumers. There is a lack in the literature on this subject.

This study includes an in-depth analysis of the possibilities for reducing energy consumption on vacuum systems and the financial savings as well. It is demonstrated that energy consumption can be reduced between 90% and 99% (depending on the application).

KEYWORDS: Vacuum system efficiency; Vacuum system carbon emissions; Vacuum system costs reduction; Gripping systems

1. INTRODUCTION

Many researchers consider carbon dioxide (CO2) to be the main current ecological danger (Abassi et al., 2022). Rising levels of carbon dioxide in the atmosphere lead to global warming which, in the long term, threatens our future on this planet.

The primary cause of this rising levels of carbon dioxide in the air is the use of fossil fuels. To reduce this use and therefore the carbon footprint, several organizations such as industrial companies have launched permanent monitoring and energy preventive, corrective and improvement actions (Osobajo et al., 2020; Prashar, 2021; M'baye, 2022a). Moreover, governments around the world continue to introduce increasingly stringent laws aimed at individuals, service companies and industry in general (for example, by permanently lowering allowable emission levels, while increasing taxes on CO2 emissions each year).

Research must continue to find solutions that can drastically reduce energy consumption and, in a large part of the case, reduce the carbon footprint of manufacturing plants in a world where electrical energy is mainly generated by power plants powered by gas, oil, and coal.

This paper focuses on the sectors using vacuum material handling systems, focusing on systems designed for impermeable or non-porous materials, such as sheet metal, plastic, and glass.

2. CALCULATION OF ENERGY CONSUMPTION AND CO2 EMISSIONS OF VACUUM SYSTEMS

Currently, the most popular vacuum technique for handling sealed materials is to use pneumatic vacuum ejectors. The handling system often consists of a robot equipped with various vacuum lifting devices and suction cups (Ross et al., 2022). There is also a lot of manual vacuum handling devices designed for waterproof objects, as well as specific production machines incorporating vacuum handling systems. This is the case, for example, of sheet metal stamping presses, laser and hydraulic cutters and glass and woodworking machines. The energy consumption of this type of vacuum handling system is defined by the quantity of compressed air that the ejector consumes to produce vacuum and to which it is often necessary to add the quantity of compressed air necessary for blow-back device to release the part quickly.

The amount of compressed air consumed by an ejector to create a vacuum depends on the number of nozzle rows, the smallest diameter of the (first) ejector nozzle and the compressed air supply pressure. The complete theoretical air consumption calculation formula for each ejector nozzle is shown below:

Volume flow (Nl/s) = Mass flow / (φ_{air} *1 000)   (1)

Mass flow (kg/s) = A*¥*$\sqrt{(P^2/(R*T)}$ (2)

<u>Where:</u>

φ_{air} = Air density at atmospheric pressure at the sea level = 101325 / (R*T)

A = Surface of the ejector nozzle (of smallest diameter).

¥ = 0,6847 = "flow coefficient" of air, used when the pressure of the compressed air is approximately 2.1 bars higher than atmospheric pressure.

P = absolute pressure (Pascal) of compressed air, zero corresponding to absolute vacuum. (6 bars = 701325 Pa).

R = gas constant for air = 287 (J/kg K)

T = air temperature (° K = Kelvin)

The specified air consumption for an ejector often differs from the theoretical value. However, the actual consumption must remain very close to the theoretical value (a small percentage difference is reasonable). Figure 1 illustrates the theoretical consumption values of conventional nozzles of different diameters at different supply pressures. The calculations are given for a temperature of 10 degrees Celsius (283.16 degrees Kelvin).

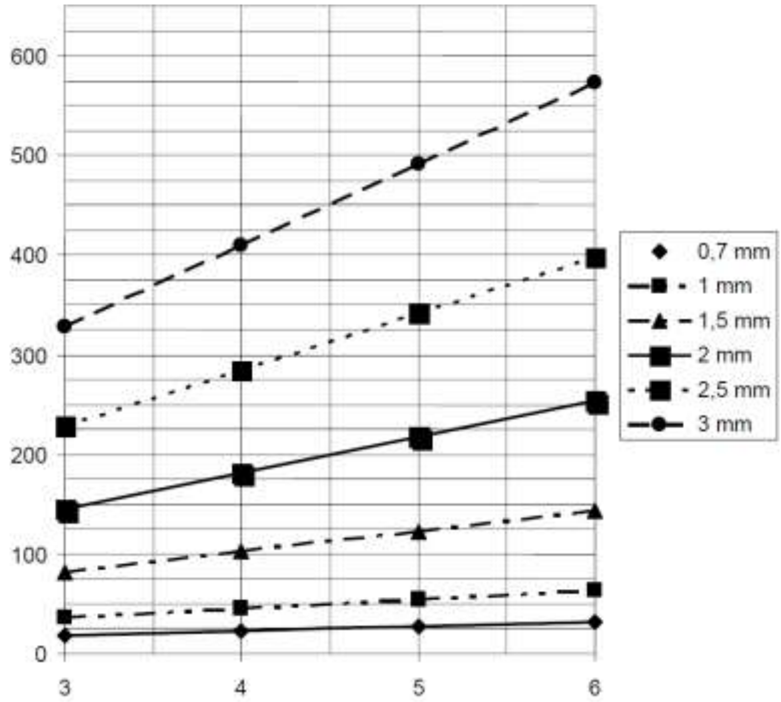

Figure 1: Air consumption in Nl/min (Y axis) depending on supply pressures in bar (X axis) and nozzles diameter

The other energy-intensive element (often overlooked,) of vacuum handling systems designed for sealed materials is the back blow function, used for rapid release of the object (Zhao & Li, 2021). The amount of air consumed during the back-blowing process is determined by the flow rate of the valve controlling the function, and the pressure used. In the case of a large and centralized ejector (with several suction cups connected to the same source), the flow levels must be very high to allow the release of the remote suction cups. In this case, flow levels of the order of 200 to 500 Nl/min between 4 and 6 bars are the norm.

In the case of a decentralized system comprising a small ejector at each suction point, the release function generally results in the obstruction of the exhaust. The air circulating in the ejector is pushed into the suction cup. Therefore, the air consumption is equal to or slightly greater than the amount of air consumed to produce the vacuum. An alternative solution consists in installing a small check valve on a decentralized system, which generally makes it possible to produce a flow of the order of 100 to 200 Nl/min between 4 and 6 bars.

In order to calculate the amount of energy consumed, it is important to know the efficiency of the compressor. A normal sized compressor, capable of producing 7 to 10 bar pressure, consumes 6 to 10 kW per cubic meter of air produced, depending on its size and output. To calculate the total amount of air consumed per year by a particular ejector, the air consumed for vacuum production is added to the air consumed for back-blowing during each cycle and the sum is multiplied by the number of cycles per year. An even more effective solution is to measure the air consumption using a flow meter over several cycles.

As stated by Foster & Bedrosyan (2014):

Coal is, by far, the largest source of energy-related CO_2 emissions globally, accounting for more than 70 percent of the total. This reflects both the widespread use of coal to generate electrical power, as well as the exceptionally high CO_2 intensity of coal-fired power. Per unit of energy produced, coal emits significantly more CO_2 emissions than oil and more than twice as much as natural gas.

Below, the CO_2 intensity by fuel:

- Coal = 0.879 kg CO_2/kWh
- Oil = 0.713 kg CO_2/kWh
- Natural gas = 0.391 kg CO_2/kWh

Taking into account only the so-called "polluting" production methods and estimating the efficiency of the compressor at 10 kW per cubic meter of air produced, the result of the calculations for the production of compressed air is 0.0391 to 0.0879 kg CO_2 /m^3.

3. HOW TO REDUCE THE CARBON FOOTPRINT OF A VACUUM SYSTEM

First, the identification of sources of energy saving goes through energy management (Muller et al., 2007; M’Baye

2022b; Prashar, 2019) and the realization of energy audits (Singha, 2007; Prashar, 2017; Mbaye 2022c).

It is obvious that the efficiency of the ejector is an important parameter to take into account in the minimization of energy/air consumption. The efficiency of an ejector is determined by the ratio between the vacuum performance (flow rate and evacuation speed) and the air consumption (Bigelow, 2017).

There are currently two main types of ejectors for vacuum-sealed material handling systems - single-stage ejectors as shown in figure 2 and multi-stage ejectors as represented in figure 3. The multi-stage model is more complex and more invasive but remains 15% to 50% more efficient (same speed/response time for less power consumption). Therefore, it is important to use a multi-stage ejector whenever possible (Mykhailyshyn et al., 2022).

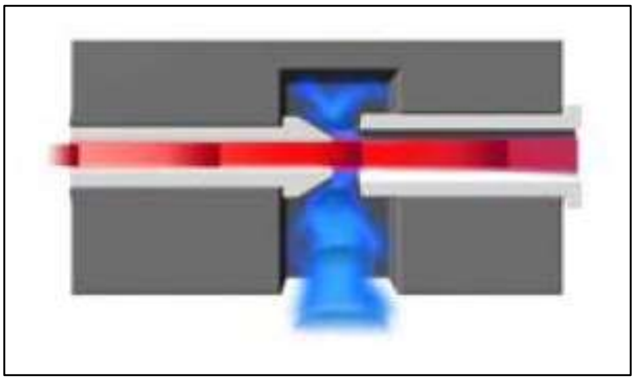

Figure 2: Single-stage ejector nozzle

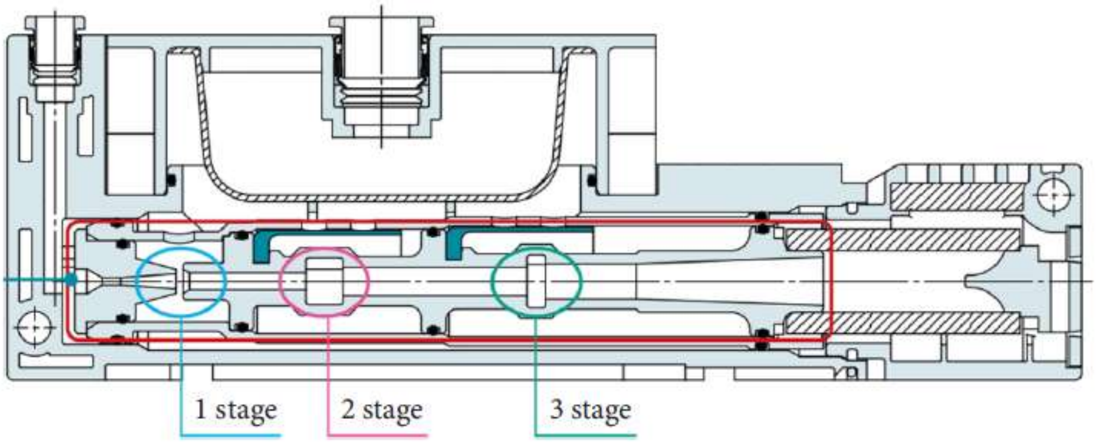

Figure 3: Multi-stage ejector (Mykhailyshyn et al., 2022)

Ejector technology for vacuum handling of sealed parts was introduced to the market as a replacement for electric vacuum pumps, primarily for reasons of ease of use and product reliability, as well as ease of adjustment of the power supplied to the pump during its use. At the time, each suction cup was equipped with small ejectors forming a decentralized system as represented in figure 4. In most cases, this type of decentralized system proves to be the most effective solution because it allows the suction to be located exactly where it is needed. Oversized ejectors are then unnecessary because it is no longer necessary to compensate for losses and superfluous volume. This system also reduces micro-leaks at joints and fittings.

However, as soon as the air-saving technology for ejectors came onto the market, a new trend developed. Ejectors called 'compacts' (or 'smart ejectors') as shown in figure 5, with integrated control functions for valves, vacuum on/off devices and air saving functions, have invaded the market. These compact ejectors are centralized so as to serve several suction cups at the same time. They are generally installed a few meters from the suction points. The air-saving function automatically stops the ejector as soon as sufficient vacuum pressure is produced and restarts the ejector to compensate for any micro-leakage from the system. One of the main advantages of this system is that the central ejector with air-saving function only works for a short time during the vacuum operating cycle, which saves energy (compared to the decentralized system used previously).

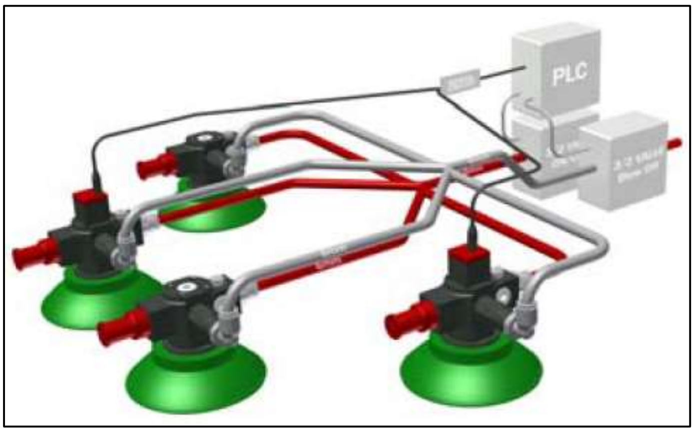

Figure 4: Small ejectors forming a decentralized system

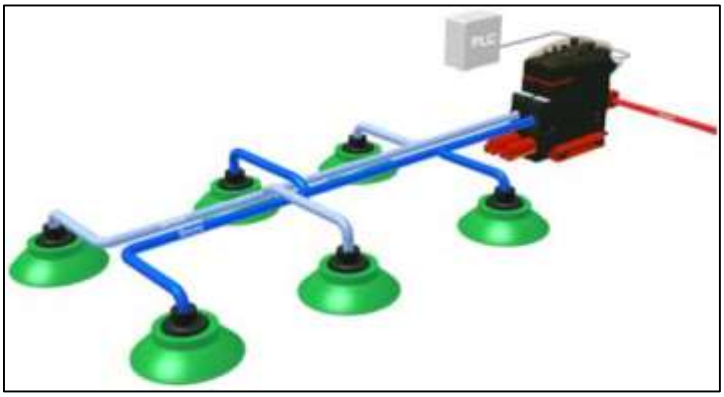

Figure 5: Centralized system with compact ejector and air saving function

With centralized compact ejectors, factors such as reliability and safety of use (one ejector per suction cup), vacuum generation speed and release of objects have to be sacrificed somewhat. The speed factor can be compensated by the installation of a very large capacity centralized ejector, which however results in greater energy consumption.

Another problem relating to the use of centralized compact ejectors lies in the fact that the counter-blowing power must be high enough to allow the object to be released fairly quickly. This problem stems from the fact that the pipes are long, and their diameter is often limited, which translates into a large consumption of air during the necessary back-blowing period. Figure 6 illustrates the typical duty cycle of a vacuum-sealed material handling application using a compact ejector with an air-saving feature.

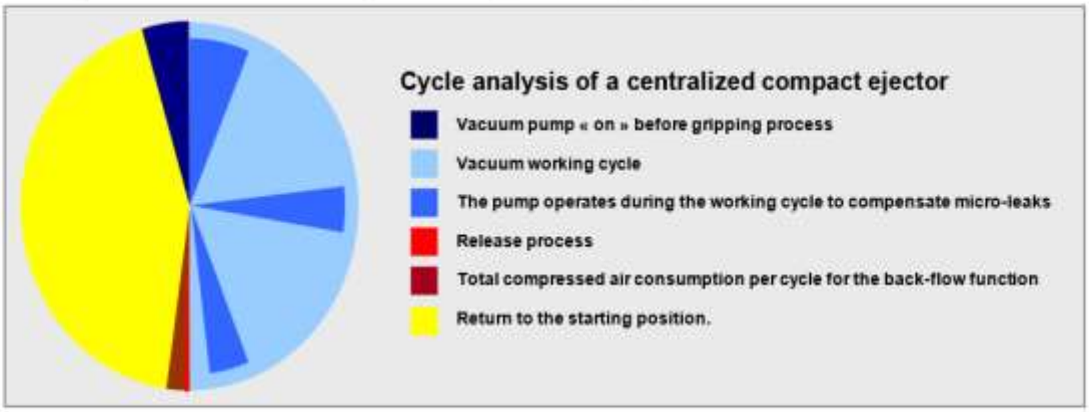

Figure 6: Cycle analysis of a centralizes compact ejector.

Air consumption occurs during the following phases (figure 6):

1. Dark blue – vacuum generation in the system starts before the gripping process to increase the gripping speed.

2. Blue – vacuum production in the system should be sufficient to compensate micro leaks at joints and fittings. Due to leaks, it is not unusual for the system to perform multiple recoveries per cycle.

3. Red – releasing the object using positive back pressure.
4. Dark red – excessive back-blowing time.

It seems obvious that even in the presence of an air saving function, a large amount of compressed air will have to be consumed during each cycle.

4. DRASTICALLY REDUCTION OF AIR CONSUMPTION AND CARBON FOOTPRINT

The solution to the problem of significantly reducing the air consumption and carbon footprint of a vacuum system lies in the use of a new decentralized compact ejector as shown in figure 7 comprising two unique functions: the Vacustat, a saving device pneumatic internal air valve, and a new blow-back valve (AQR) that uses ambient air to quickly release the handled part.

The volume of a suction cup is low enough to require only ambient air. In other words, the system does not require compressed air for the release function and includes an automatic air saving device.

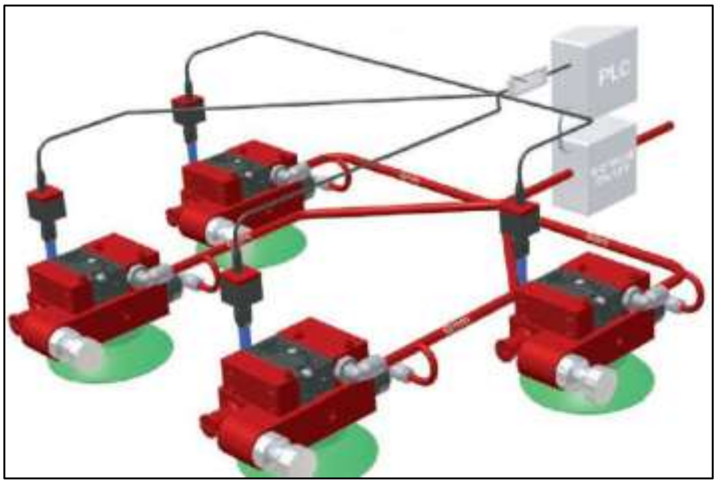

Figure 7: New patented Vacustat-COAX® system using AQR technology

AQR (Fast Atmospheric Backflow Valve), as seen in figure 8, is used in a decentralized vacuum system. The AQR valve eliminates the requirement for double piping for each remote unit, resulting in a smoother network and lower costs by eliminating an additional valve.

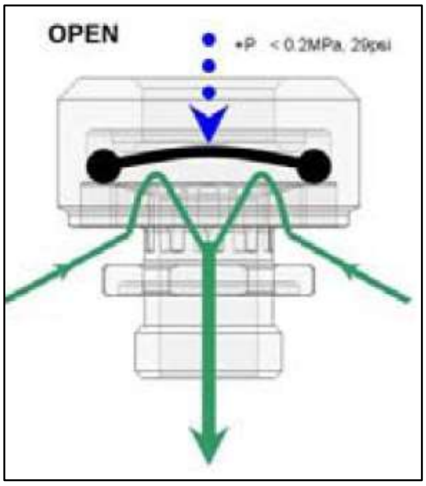

Figure 8: Fast Atmospheric Backflow Valve

This design offers all the advantages of a decentralized ejector system in terms of reliability, safety, and speed (response and release). Air and energy consumption is also very low. The loosening of objects takes place without the consumption of compressed air and the air-saving function does not have to compensate micro-leaks from various joints and fittings.

The volume is low enough to allow (almost instantaneous) the triggering of the air saving function. The period of preparation of the ejector before gripping is almost eliminated and there is no need to produce a vacuum in advance in the system. The system will therefore work even faster.

As shown in figure 9, the pump only operates for a very short time.

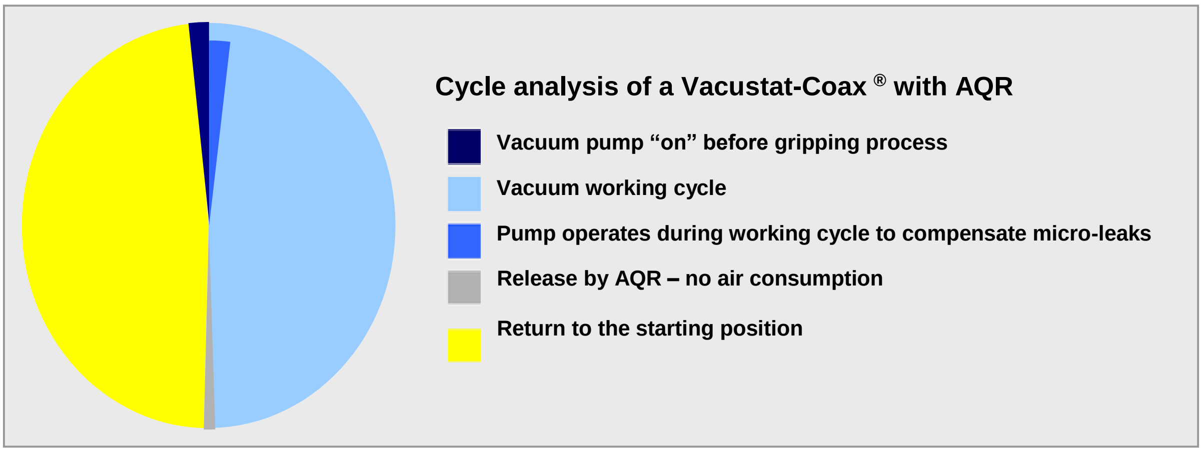

Figure 9: Cycle analysis of a Vacustat-Coax® with AQR

Below a focus on a typical vacuum handling application for sealed products:

Under the following conditions and requirements:

- Cycle time: 10s
- Operating hours per year: 6,000 h
- Vacuum production cycle: 5s
- Number of suction cups with a diameter of 75 mm: 4
- Response time: max. 0.1 to 0.2s
- Release time: <0.1s

Result depending on the solution adopted:

- Previously developed decentralized solutions use approximately 25,000 to 40,000* m3 of air per year
- A compact ejector with energy-saving function reduces air consumption to approximately 15,000-20,000* m3 of air per year.
- The Vacustat-COAX®-AQR solution uses approximately 1,000 m3 of air per year.

*The difference is significant because the result depends on whether a single-stage or multi-stage ejector is used.

Under these conditions, it is possible to reduce energy consumption by 90 to 99%. It is estimated that 15,000 to 40,000 m3 of air correspond practically to 586 to 3,516 kg of carbon dioxide emissions if the electrical energy is generated by a gas, oil, or coal-fired power plant, considering a single application/single post.

A typical car factory can have up to 400 of such applications. The carbon footprint of vacuum handling in these plants can reach between 180,000 and 480,000 kg in the presence of traditional vacuum technology (depending on the conditions indicated above). Using a Vacustat-COAX® technology with AQR can reduce the carbon footprint to just 12,000 kg.

By comparison, the average amount of CO2 produced by a car is 180g/km. The reduced annual carbon footprint of a car factory using the latest vacuum handling technology corresponds to the emission of a car driving a distance of 900,000 to 2,600,000 km.

5. ENERGY COST REDUCTION AS A BONUS

Currently, European companies pay a tax on CO2 emissions between $0.015 and $0.03 per kg (Zhang et al., 2016). By adopting the latest vacuum handling technology, an automotive factory can save over $15,000 in taxes alone. It's a important advantage when there is a high probability that taxes continue to increase.

But ultimately, the reduction in power consumption is the biggest long-term saving in operating costs. In general, the cost of producing compressed air in a plant using a normal size compressor (considering cost per kWh, life cycle, interest rate, purchase price, maintenance costs, annual operating hours, etc.) are between 0.01 and 0.012 dollar per cubic meter of air.

A car factory with 400 handling stations can easily save $67,000 to $187,000 per year in energy consumption by adopting the latest vacuum technology.

6. CONCLUSION

In many industrial processes, the energy efficiency of the vacuum technology used affects the overall efficiency of the process. An overly narrow view of the performance data from individual vacuum pumps is usually misleading. Numerous factors and the characteristics of the vacuum technology used need to be taken into account to optimize the efficiency of vacuum generation.

Coupled vacuum pumps (with or without vacuum boosters) or centralized vacuum systems often offer the best solution for providing the required vacuum in the process with the lowest energy consumption. As vacuum pumps also generate heat due to their physical properties, aspects like the need for additional cooling and possible heat recovery also play a role in terms of efficiency.

As demonstrated in this paper, it is therefore necessary to consider the overall process and coordinate the vacuum technology with the process technology for efficient vacuum generation.

REFERENCES

1. Abbasi, K.R., Kirikkaleli, D. & Altuntaş, M. Carbon dioxide intensity of GDP and environmental degradation in an emerging country. Environ Sci Pollut Res 29, 84451–84459 (2022). https://doi.org/10.1007/s11356-022-21679-9
2. Bigelow W. C., Some Interesting Facts About Vacuum Pumps and Rate of Evacuation, Microscopy Today, Volume 25, Issue 4, 1 July 2017, Pages 28–33, https://doi.org/10.1017/S1551929517000591
3. Foster, Vivien; Bedrosyan, Daron. 2014. Understanding CO2 Emissions from the Global Energy Sector. Live Wire, 2014/5. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/17143 License: CC BY 3.0 IGO
4. M’baye, A. (2022a). Carbon Emission Efficiency Best Practices: A Case Study in an Industrial Site. Journal of Energy Research and Reviews, 10(3), 10–23. https://doi.org/10.9734/jenrr/2022/v10i330256
5. M’Baye, A. (2022b) Energy Performance Management in an Industrial Site: Definition and Application of a Specific Methodology for Carbon Emissions Reduction. Low Carbon Economy, 13, 148-162. https://doi.org/10.4236/lce.2022.133008
6. Mbaye, A. (2022c). Review on Energy Audit: Benefits, Barriers, and Opportunities. American Journal of Energy and Natural Resources, 1(1), 45–58. https://doi.org/10.54536/ajenr.v1i1.1054
7. Muller Damien C.A., Marechal François M.A., Wolewinski Thomas, Roux Pieter J., An energy management method for the food industry, Applied Thermal Engineering, Volume 27, Issue 16, 2007, Pages 2677-2686, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2007.06.005
8. Mykhailyshyn, R., Savkiv, V., Maruschak, P., & Xiao, J. (2022). A systematic review on pneumatic gripping devices for industrial robots. Transport, 37(3), 201–231. https://doi.org/10.3846/transport.2022.17110
9. Osobajo, O.A.; Otitoju, A.; Otitoju, M.A.; Oke, A. The Impact of Energy Consumption and Economic Growth on Carbon Dioxide Emissions. Sustainability, 2020, 12, 7965. https://doi.org/10.3390/su12197965
10. Prashar Anupama (2017), Adopting PDCA (Plan-Do-Check-Act) cycle for energy optimization in energy-intensive SMEs, Journal of Cleaner Production, Volume 145, Pages 277-293, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2017.01.068
11. Prashar Anupama (2019), Towards sustainable development in industrial small and Medium-sized Enterprises: An energy sustainability approach, Journal of Cleaner Production, Volume 235, Pages 977-996, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2019.07.045
12. Prashar Anupama (2021) Eco-efficient production for industrial small and medium-sized enterprises through energy optimisation: framework and evaluation, Production Planning & Control, 32:3, 198-212, DOI: https://doi.org/10.1080/09537287.2020.1719714
13. Ross S., O. Korostynska O., Cordova-Lopez L.E., Mason A., A review of unilateral grippers for meat industry automation, Trends in Food Science & Technology, Volume 119, 2022, Pages 309-319, ISSN 0924-2244, https://doi.org/10.1016/j.tifs.2021.12.017
14. Singhal, D. K. (2007). Energy Audit of Vacuum System. IPPTA, 19(2), 129.
15. Zhang Kun, Wang Qian, Liang Qiao-Mei, Chen Hao, A bibliometric analysis of research on carbon tax from 1989 to 2014, Renewable and Sustainable Energy Reviews, Volume 58, 2016, Pages 297-310, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2015.12.089
16. Zhao J, Li X. Two-dimensional pressure field and backflow in the annular skirt of vortex gripper. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2021;235(20):51-57. https://doi.org/10.1177/0954406220974044