INCREASE OF ENERGY EFFICIENCY IN VACUUM HANDLING SYSTEMS BASED ON BIOMIMETIC PRINCIPLES

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ABSTRACT

Vacuum handling is a widespread technology in automated production systems for gripping of workpieces. Unfortunately, this solution accounts for a considerable share of industrial energy consumption. This consumption is mainly due to the losses in the involved steps like air compression, distribution, vacuum generation and gripper suction. However, the energy efficiency of vacuum handling systems is still relatively unexplored. The consortium partners are working together in the *BiVaS* project, which is funded by the Federal Ministry for Economic Affairs and Energy (BMWi). In this project, the drawback of high energy consumption is approached by the development of an energy-efficient ejector, a biomimetic suction gripper as well as on system integration and the development of energy-efficient operating strategies and their energetic balancing in order to reduce the consumption of compressed air by 20 %. This reduction will be quantified experimentally in a pilot plant benchmark, where a realistic handling process is developed and examined. This paper shows the state of the art focusing on energy consumption of vacuum handling technology and the behaviour of the involved components during different handling operations. Furthermore, first biomimetic concepts and an estimation of the increase of energy efficiency will be presented for the running project.

Keywords: Vacuum Handling, Energy Efficiency, Bioinspiration, Biomimetics, CFD optimization, Level set, adjoint variable

1. INTRODUCTION

Due to the rising cost of energy, worldwide mitigation of carbon footprint and social demand for sustainable and renewable orientation of industrial activities, efficient energy usage is mandatory. Improving the vacuum handling technology can lead to drastic energy saving possibilities in pneumatic systems. In this regard, the selection of appropriate components for production and the correct system design play important roles.

Energy efficiency in the field of vacuum handling technology is still low, due to the

transformation of electrical energy in compressed air and, subsequently, the transformation of compressed air into vacuum. Besides the vacuum generation, also the further infrastructure, the workpiece, the suction cups and of course the process parameters are influencing the energy consumption of a vacuum gripper in general, as mentioned above.

First research projects have already tried to tackle the existing problems (e.g. [1] and [2]), for example regarding pneumatically driven vacuum generators as a key component (e.g. [3-9]). Due to features like air saving function and others for

influencing the handling process, these research results are not significant enough to evaluate entire handling processes under real production conditions in use.

The predominant component to generate vacuum in industrial handling processes is a pneumatically driven vacuum ejector operated with compressed air. **Figure 1** shows typical energy conversion chains with compressed air supply (compressor and distribution), vacuum generation (ejectors) and transformation in holding force (vacuum gripper).

Figure 1: energy transformation and losses in vacuum handling (based on [10], [11])

Focusing on the compressed air supply in medium-sized companies, the efficiency ratio due to losses ranges only between 1 % [10] and 10 % [11], so that the energy supply for the genuine gripping system is one of the most expensive forms of energy [11]. By using pneumatically driven vacuum gripping systems, this already low efficiency ratio is further reduced, because the following energy conversion step with ejectors can not achieve higher efficiency ratios than approx. 20 %, as shown by own investigations. Besides the lossy transformation steps there are even further losses due to leakage and the process itself. At the end of a gripping process, less than 1 % of the used energy is available for the real handling task. If the inherent advantages of vacuum gripping technology should be also used in the future, it is necessary to increase their energy efficiency. For this increase, it is mandatory to optimize the vacuum generation as well as the transformation in a holding force with a gripper and as well as the operating method of the system significantly.

The economic importance of vacuum handling technology is shown by the following estimation: In 2012, the industrial power consumption of the Federal Republic of Germany amounted to 213 TWh, with a share of 7 % (16 TWh) for compressed air supply. An important share of this

air consumption reveals to “vacuum air” – compressed air to generate a vacuum [11]. Own research has shown, that this consumption amounts for approx. 5-20 %, depending on the industry segment. Table 1 shows the resulting economical energy costs and carbon emissions (0.1 €/kWh, 576 g CO₂/kWh [12]).

Table 1: Scenario for the share of “vacuum air” in the energy budget of Germany

Compressed Air [GWh]	Costs [Mio €]	CO ₂ -emissions [Mt]
0.81	81	0.467
1.62	162	0.933
2.43	243	1.400
3.24	324	1.866

Suction cups are the connecting device between handling and workpiece. During the gripping process, a vacuum is generated between suction cup and workpiece. The holding force of the gripper is proportional to the difference of pressure and the effective area impacted by the vacuum. For generating a vacuum between suction cup and workpiece, the system has to be sealed against ambient pressure, because leakage between the suction cup and workpiece will increase the air consumption of the gripping system. Also high amounts of dead volumes in suction cups, vacuum generators or hoses and fittings lead to an increasing energy demand.

Additionally, process safety is very important in handling processes and, therefore, requires a fail-safe gripper-workpiece-connection.

The air consumption of such systems can be reduced by using so-called “compact ejectors”, which allow stopping vacuum generation by their “air saving function” to stop vacuum generation when the predefined vacuum level is reached. As mentioned, these “compact ejectors” can reduce the air consumption up to 90 % [13-14]. Furthermore, there were different approaches for an energy efficient operating method in the past [15-17].

For a holistic approach, all factors influencing the air consumption are being investigated in *BiVaS*, as long as these parameters can be influenced by the distributor of the vacuum technology. E.g., leakage in the infrastructure, like distribution or the compressor itself, is not in focus.

For this holistic approach, new and optimized suction cups, vacuum generators and new ways to operate vacuum handling systems will be developed.

First, a biomimetic approach incorporating the basic investigation and abstraction of adhesion principles in plants and animals and the subsequent transfer of working principles into improved suction cups was started.

2. BIOMIMETIC OPTIMIZATION

Energy-efficient (suction) adhesion not only plays an important role in industrial applications, it as well represents a selective evolutionary advantage in various organisms. Consequently, a wide variety of different taxa have evolved numerous adaptations towards energy-efficient attachment mechanisms on various substrates over time. Since the same physical laws apply to both biological and technical suction devices (if used under comparable surrounding conditions), the analysis of the form-structure-function relationships of such biological adaptations and the transfer into technical adhesive systems by using a biomimetic approach is extremely promising to tackle the challenges described above.

Previous studies of biological suction systems have mainly been carried out on aquatic animals, especially in molluscs (particularly cephalopods like octopi and squids), arthropods (e.g. torrent-living insect larvae or diving beetles), fish (notably remora and clingfish) and lamprey. The adhesive organs of these animals are usually suction discs, which are used in the hunt for prey, in parasitic nutrition, and in copulation. The margins of biological suckers are usually very compliant, oftentimes microstructured and characterised by marginal protuberances (villi), which increase the overall adhesion due to contact splitting and compensate for surface irregularities thereby minimizing leakage currents between the suction chamber and the environment [18]. For instance, the microstructured suction disc rim of *Octopus vulgaris* is characterized by an average roughness of $R_a = 11.3 \mu\text{m}$, which enables a good form fit to the substratum [19]. Additionally, a variety of other animals, such as the Northern clingfish, secretes mucus along the rim of their suction organ to seal the suction chamber efficiently [20]. Last but not least, a good form fit with the

substrate is achieved through a high mechanical adaptability of the sucker margins. In particular, the suction disc rim of the octopus consists of extremely soft tissue (average modulus of elasticity, $E = 7.7 \text{ kPa}$) and can therefore adapt very well to surface asperities [19].

However, energy is not only required for establishing a pressure difference between the inside of a suction device and its surroundings, often energy is also essential for the maintenance of the overall adhesion. Again, some biological role models utilize functional principles which demonstrate that additional energy is not necessarily required to maintain suction adhesion for secured attachment. For example, the octopus does not exert any additional muscle power to stay attached to an object. Here, the deformation of an acetabular protuberance encloses a water torus inside each sucker during the attachment process. Hence, the state of adhesion is solely maintained by the cohesive force of the retained water and by frictional forces between the surfaces of the protuberance and the inner suction cup walls which counterbalance the elastic restoring force of the deformed protuberance [19, 21]. Such locking mechanisms are very promising and could also be implemented into a biomimetic suction device.

While quite a lot of preliminary work has already been done in the field of aquatic suction adhesion, to date very little is known about how (partly) terrestrial animals with suction discs achieve their attachment and which behavior-based, morphological and biomechanical adaptations exist here [18, 22]. Suitable terrestrial role models include, for example, land leeches that comprise several systematic groups (e.g. Haemadipsidae) and slug caterpillars (Limacodidae) [23]. Moreover, a very versatile suction adhesion system on two different suckers (anterior and posterior) that functions both under water and in air is found in medicinal leeches (*Hirudo verbana*) [24]. Here, experiments utilizing light and scanning electron microscopic techniques revealed that both the anterior and the posterior suction disc of *H. verbana* lack pronounced microstructures (e.g. villi), which are otherwise often to be found on the suckers of other organisms. Furthermore, it was possible to accurately resolve the attachment and detachment processes of these suction discs and to analyse corresponding suction cup deformations using high-speed videography. Interestingly, in

addition to other characteristics, a special behaviour was observed, according to which the leech always initiates the attachment process of its suckers by bringing their everted central parts into contact first, thereby preventing the inclusion of fluid inside the suction chambers. Therefore, a reduction of the sucker's dead volume, which is already implemented in the design or takes place before the suction cup is positioned on a given surface or work piece, can again lead to an increase in efficiency, since less or no energy has to be invested for evacuating enclosed fluids ("dead volume").

Comparative attachment force measurements of the two suction cups on differently structured surfaces in air and under water also highlighted that medicinal leeches developed a very versatile and fail-safe (suction) adhesion mechanism. In particular, the enormous adaptivity of the system becomes evident when the leech crawls upside down along a fine metal wire mesh [24]. This observation hints towards the fact that the medicinal leech employs different physical adhesion principles. In this context, the application of multiple physical principles within one adhesive system is not uncommon in nature (as can be seen in the systems of e.g. clingfish, octopi and limpets) and can certainly be regarded as a form of functional resilience which is, however, absent in current technical suction devices.

Another advantage of a biomimetic approach is that the optimization of a technical system does not necessarily have to use form-structure-function relationships that originate from only one role model and correspond to the same field of application as the biological system itself. Even principles of operation of other adhesive mechanisms can be transferred to improve certain aspects of a technical suction device, for example, to accomplish a functionalization of the contact surface. Clingfish, for instance, possess a strong hierarchical structuring at their suction rims, which lead to an increase in friction, which in turn counteracts deformation of the edges and thus failure of the whole system [25]. Furthermore, the toe pads of tree and torrent frogs are micropatterned in a way that enables an oriented drainage of obstructive fluids from the contact zone, thereby improving the adhesion of a system on heavily wetted surfaces [26-29].

To date, the majority of the afore-mentioned biological principles is not implemented in

standard technical suction devices. Conventionally, technical suckers consist of polymers exhibiting material properties that differ from those of potential biological concept generators. In addition, they usually exhibit considerable dead volumes, no microstructuring and generally no additional fluids such as mucus or other liquids that improve their sealing capability. Although there are already a number of biomimetic studies that utilize natural principles in order to optimize technical (suction) adhesion systems [30-32], there is still a lot of innovation potential for the development of biomimetic suction cups.

3. OPTIMIZATION OF EJECTORS

Complementing the research on biomimetic suction process, also the development of an innovative ejector principle that works significantly more efficiently than common ejectors in terms of supply pressure and energy consumption is considered. Research on the achievable performance potentials of low-pressure ejectors, by the use of numerical methods is conducted.

For identifying an optimal design for efficiency enhancement, the parametric shape and topology optimization like shown in **Figure 2** are suggested methods.

Figure 2: Optimization methods

We suggest applying level set topology optimization to find the optimum topology in order to find the optimal geometry for the desired, more efficient pneumatic ejector.

The level set method (LSM) is a numerical technique for tracking interfaces and shapes, which can travel through the control volumes. The interface is the outline that separates the solid body and the surrounding fluid. This interface will move with a normal speed that comes from the surface gradient.

As can be seen in **Figure 3**, $\phi(\vec{x}, t)$ the level set function which is defined on the whole domain. $\Gamma(t)$ defines the contour of the geometry where $\phi(\vec{x}, t) = 0$. $\phi(\vec{x}, t) < 0$ and $\phi(\vec{x}, t) > 0$

gives the location of air and the solid body, respectively [33].

$$\begin{cases} \phi(\vec{x}, t) < 0 & \text{when } \vec{x} \in \Omega \\ \phi(\vec{x}, t) = 0 & \text{when } \vec{x} \in \partial\Gamma(t) \\ \phi(\vec{x}, t) > 0 & \text{when } \vec{x} \in R^n \setminus \bar{\Omega} \end{cases} \quad (1)$$

Figure 3: Level set contour of geometry

To follow the change of the contour, the change of the time-dependent zero level set is considered.

$$\frac{d}{dt} \phi(\vec{x}(t), t) = 0 \quad (2)$$

$$\frac{\partial \phi}{\partial t} + \nabla \phi \frac{d\vec{x}}{dt} = 0 \quad (3)$$

Where:

$\frac{\partial \phi}{\partial t}$ is temporal change of the level set function, $\nabla \phi$ is the gradient of the level set function, and $\frac{d\vec{x}}{dt}$ is the speed in the outward normal direction [33], **Figure 4**.

Figure 4: Contour normal velocity

With the combination of the finite element method and efficiency approaches, LSM can be used in topology optimization of an ejector.

However, in LSM the gradient of the target function is used as the normal speed for renewing the level set function. The approximation of the gradient by numerical differentiation is time consuming due to the high number of parameters and requires high computational costs. The direct

derivation of the LSM function can be replaced by a alternative formulation of topology optimization.

For this purpose, a coupling with another numerical method is proposed. The adjoint variable approach, which provides efficient sensitivity information of derivatives, is combined with level set methodology. In gradient-based optimization techniques, the goal is to minimize a suitable cost or objective function with respect to a set of design variables. The adjoint variable method is a very efficient method to compute the cost function gradient, which allows for the solution of general sensitivity analysis problems governed by fluid dynamics models.

Search for $\partial\Gamma = \{\vec{x}(t) | \phi(\vec{x}(t), t) = 0\}$

Minimize f

Subject to $g(\phi, B) = 0$

$$F(\phi, B) = f(\phi, B) + z^T \times g(\phi, B) \quad (4)$$

$$z^T = -\frac{\partial F}{\partial A} \times \left(\frac{\partial g}{\partial A}\right)^{-1} \quad (5)$$

Where z^T is the adjoint variable, f is the objective function, B can parametrize boundary and initial conditions or material properties, and g represents the relation between ϕ and B .

For this purpose, a proper selection of the objective function based upon energy consumption of pneumatic ejector is necessary.

3.1. Objective function

There are many possibilities to be found in the literature on how the efficiency of an ejector can be obtained; some of them are mentioned in the following:

Entrainment ratio

The ejector performance is often measured by the entrainment ratio (λ) defined as:

$$\lambda = \frac{\dot{m}_3}{\dot{m}_1} \quad (6)$$

Figure 5: A schematic of an ejector

Where $\dot{m}_1$ is inlet mass flow rate from primary nozzle and $\dot{m}_3$ is intake mass flow rate from suction chamber according to **Figure 5**. The entrainment ratio is related to the coefficient of performance of the ejector by the following expression:

$$\eta = \lambda \frac{\Delta h_3}{\Delta h_1} \quad (7)$$

For a given ejector, the entrainment ratio is affected mostly by its geometry [34]. The ejector performance ratio decreases with increasing generator pressure [35]. Another important geometrical issue is the primary nozzle exit position. Eames [36] claimed that the influence of the nozzle exit position on λ could be as high as 40 %.

Components efficiency

In order to include irreversibility associated with the components, friction losses were introduced by applying isentropic efficiencies to the primary nozzle, suction, and diffuser. Therefore, efficiency of different parts of an ejector can be defined as below:

Nozzle [37]:

$$\eta_{nozz} = \frac{h_1 - h_{nozz,ex}}{h_1 - h_{nozz,ex,isn}} \quad (8)$$

Suction chamber [38]:

$$\eta_{suc} = \frac{h_3 - h_{nozz,exit}}{h_3 - h_{nozz,exit,isnt}} \quad (9)$$

Mixing chamber [39, 40]:

$$\eta_{entr,mix} = \frac{(\dot{m}_1 + \dot{m}_3) \cdot v_{mix}}{\dot{m}_1 \cdot v_{nozz,exit} + \dot{m}_3 \cdot v_{sec,nozz,ex}} \quad (10)$$

Energy conversion efficiency

In practice it is not possible to assign the energy consumption of single consumers directly to electrical energy input used for the system of compressed air supply network [3]. Therefore, the first law of thermodynamic is applied with assumption of adiabatic process and considering air as an ideal gas:

$$\eta = \frac{P_{32}}{P_{12}} \quad (11)$$

Where

$$P = \sum_{out} \dot{m}_o \left(c_v T + RT + \frac{1}{2} \left(\frac{\dot{m}_o RT}{p} \right)^2 \right)_o - \sum_{in} \dot{m}_i \left(c_v T + RT + \frac{1}{2} \left(\frac{\dot{m}_i RT}{p} \right)^2 \right)_i \quad (12)$$

Because the ejector has no interface for output of mechanical power, and the kind of the state change within the ejector is unproven and difficult to predicate, direct application of first law, with shown system boundary in **Figure 6**, is not suitable for energy efficiency determination.

Figure 6: Ejector control volume

Exergy efficiency

With the use of exergy, the non-reasonable assumption of isentropic state change can be avoided. Because the exergy is characterized as the maximum useful work, the surrounding itself has to be in thermodynamic equilibrium [3]. According to ISO 6358 [41] $T_0 = 293.15 \text{ K}$ is a technical exergyless reference condition.

The exergy of a fluid flow can be determined with application of the first and second law of thermodynamics [42] and with consideration air as an ideal gas.

$$\dot{E}(T, p) = \dot{m} \left[(\Delta T \cdot c_p^{ig} - T_0 \cdot c_p^{ig} \cdot \ln \frac{T}{T_0} + T_0 \cdot R \ln \frac{p}{p_0} + \frac{1}{2} v^2) \right] \quad (13)$$

The exergetic conversion efficiency of an ejector can be described as in (14) and (15).

$$\eta_{exergy} = \frac{\dot{E}_{out}}{\dot{E}_{in}} \quad (14)$$

$$\eta_{exergetic} = \frac{\dot{m}_3 \left[(T_3 - T_0) c_p^{ig} - T_0 \cdot c_p^{ig} \cdot \ln \frac{T_3}{T_0} + T_0 R \cdot \ln \frac{p_0}{p_3} + \frac{1}{2} \left(\frac{\dot{m}_3 R T_3}{p_3 A_3} \right)^2 \right]}{\dot{m}_1 \left[(T_1 - T_0) c_p^{ig} - T_0 \cdot c_p^{ig} \cdot \ln \frac{T_1}{T_0} + T_0 R \cdot \ln \frac{p_1}{p_0} + \frac{1}{2} \left(\frac{\dot{m}_1 R T_1}{p_1 A_1} \right)^2 \right]} \quad (15)$$

To develop a novel methodology for boundary design of a pneumatic ejector, an algorithm will be implemented with the use of level set methods to minimize energy losses. It is expected that level set based topology optimizations are capable of handling the ejector optimization and will provide useful tools for design of ejectors.

According to efficiency approaches, the most eligible method to optimize the ejectors is based on exergy which covers almost all the influential parameters. To find the desirable higher-efficient ejector, $f(\phi, B) = 1 - \eta_{exergetic}$ can be

considered as objective function to be minimized during material distribution optimization.

4. OPERATING STRATEGIES FOR ENERGY-EFFICIENT VACUUM HANDLING PROCESSES

The process design can have a huge influence on the resulting energy consumption. In general, vacuum handling processes can be divided into four process phases (**Figure 7** top) in accordance with [43]. Potential for energy savings can be identified in each of the first three main phases (**Figure 7**, bottom).

In the evacuation phase, a feasible strategy is to evacuate most of the air by pressing the gripper onto the surface of the part to be handled. This enables a reduction of the dead volume that must be actively evacuated by operating an ejector. Also, high consumption of compressed air for a safe blow-off of the grasped object can be avoided by adequate ventilation mechanisms.

However, the highest potential for energy savings is attributed to leakage prevention. In practice, it is technically feasible to compensate for a small leakage air flow by an ejector with an

In order to prevent permanent leakage between gripper and object prior to the operation of the handling process, it is necessary to enable the knowledge-based design of both the gripping system and the handling process. For the efficient acquisition of such knowledge, a method for the comparable characterization of suction grippers has been developed at IWF. In this method, suction grippers are tested in combination with multiple test objects with parametrized primitive geometries (**Figure 8**).

Figure 8: Parametrized primitive objects for standardized gripper tests

Figure 7: Process phases of vacuum handling processes and corresponding potentials for energy savings

adequate suction capability, as it is highly unlikely to achieve perfect sealing and thus zero leakage. Yet, permanent excessive leakage requires continuous vacuum generation and therefore leads to high energy consumption. Up to now, these uncertainties are encountered with adequate safety factors with which both the gripping system and the process parameters are overdimensioned.

This allows for the evaluation of specifically designed experiments, for example the investigation of the leakage during the evacuation phase.

Although it is intuitive that the sealing in combination with a plane will potentially be significantly better than in the case of a curved surface, through application of these standardized experiments, novel gripper designs could be

designed specifically to offer behavior opposing to standard grippers.

With this gripper-specific knowledge, the gripper system can be designed for an application-specific handling task with regard to the optimal positions of the required suction grippers. Such an optimization problem becomes increasingly complex with a rising amount of required grippers. In addition, the geometry of the part to be handled significantly influences the complexity, as well.

As soon as the gripping system has been designed, the gripper-specific knowledge can be applied for process design. Based on the allowed duration for one entire handling cycle, a certain duration can be attributed to each process phase as depicted in **Figure 7**. This directly influences the required ejector model, since the evacuation must be completed within the defined time interval. Furthermore, the accelerations which occur due to the defined robot trajectory result in loads that act upon the gripper-object interface (GOI).

Therefore, the robot trajectory can be designed to ensure that process-induced forces do not exceed the gripper-specific limitations. Finally, this enables to significantly reduce or even eliminate the currently applied safety factors which results in significant decreases of the energy consumption.

5. CONCLUSION AND OUTLOOK

As mentioned, energy efficiency of vacuum handling systems is still low. But there are several measures to optimize the energy consumption by designing new components and improving the process itself. Due to fact that the *BiVaS* project is still ongoing, there could only be presented approaches and some first results. Based on these results, we anticipate a reduction of the energy consumption in vacuum handling of up to 20 %.

NOMENCLATURE

A	Surface
B	Adjoint parameter
c	Specific heat
e	Exergy
f	Objective function
g	
h	Enthalpy
I_g	Ideal gas

IWF	Institute for machine tools, TU Braunschweig
LSM	Level set method
$\dot{m}$	Mass flow
p	Pressure
R	Gas constant
R_a	Average roughness
s	Entropy
T	Temperature
t	Time
v	Velocity
x	Coordinate
z^T	Adjoint variable
ϕ	Level set function
λ	Entrainment ratio
η	Efficiency
Γ	Geometry contour

REFERENCES

- [1] Fritz, F. (2017). Ein Modell zur energetischen Analyse und Bewertung von Vakuum-Greifsystemen. Dissertation. Stuttgart University, Shaker, 2017
- [2] Kuolt, H. (2013). Automatisierung in der Produktionstechnik – Herausforderungen und Lösungen zur Steigerung der Energieeffizienz von Handhabungssystemen. Stuttgart, GSaME Jahrestagung, 21.03.2013
- [3] Fritz, F., von Grabe, C., Kuolt, H., Murrenhoff H. (2013). Benchmark of existing energy conversion efficiency definitions for pneumatic vacuum generators. In: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering", Singapore, 2013.
- [4] Kuolt, H., Gauß, J., Schaaf, W., Winter, A. (2016). Optimization of pneumatic vacuum generators – heading for energy-efficient handling processes. In: Proceedings of the IFK2016, Dresden, S. 267-280
- [5] Löser, H. R. (1966). Untersuchungen an ein- und zweistufigen Überschallejektoren mit zylindrischer Mischkammer, Darmstadt, 1966
- [6] Leistner, G. (1966). Experimentelle und theoretische Untersuchungen an einem Hochtemperatur-Überschallejektor mit zylindrischer Mischkammer, Darmstadt, 1966
- [7] Lucas, C., Rusche, H., Kaiser, C. Schröder, J. (2014). Numerical investigation of a two-phase CO₂ ejector. International Journal of Refrigeration, Bd. 43, p. 154–166, 2014.
- [8] Alimohammadi et al. (2013). A Validated Numerical-Experimental Design Methodology for a Movable Supersonic Ejector Compressor

- for Waste-Heat Recovery. *Journal of Thermal Science and Engineering Applications*, 2013
- [9] Opgenorth, M. J., Sederstrom, D., McDermott, W., Lengsfeld, C. S. (2012). Maximizing pressure recovery using lobed nozzles in a supersonic ejector. *Applied Thermal Engineering*, Bd. 37, p. 396–402, 2012
- [10] Schestag, R. (2015). *Betrieblicher Umweltschutz in der Metallbearbeitung*. Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, Stuttgart, 2015
- [11] EnEffAH (2012). *Energieeffizienz in der Produktion im Bereich Antriebs- und Handhabungstechnik*, Brochure of BMWi Project EneffAH, 2012.
- [12] Icha, P. (2013). *Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2012*, Umweltbundesamt, Hrsg., Deassa-Roßlau, 2013
- [13] J. Schmalz GmbH (2017). *Kompaktejektoren X-Pump SXPi* Available: <https://www.schmalz.com/de/vakuumtechnik-fuer-die-automation/vakuum-komponenten/vakuum-erzeuger/kompaktejektoren/kompaktejektoren-x-pump-sxpi-sxmpi-mit-io-link>. Access:14 2 2017].
- [14] Kuolt, H. (2015). *Verfahren zum Betreiben einer Unterdruckhandhabungsvorrichtung, sowie Unterdruckhandhabungsvorrichtung*. 2015.
- [15] Wigren, G. (2015). *Object-sensing valve for a vacuum gripper*, 2015.
- [16] Mayer, M., Anderle, J., Wirtl, H. (2017). *Vakuum-Greifvorrichtung und Verfahren zum Betreiben einer Vakuum-Greifvorrichtung*, 2017.
- [17] Holecek, T., Eisele, T., Kuolt, H, Frey, C (2015). *Method for operating a vacuum generator and a vacuum generator*. 2015
- [18] Ditsche, P. & Summers, A.P. (2014). Aquatic versus terrestrial attachment: water makes a difference. *Beilstein J. Nanotechnol.*, 5: 2424–2439.
- [19] Tramacere, F., Kovalev, A., Kleinteich, T., Gorb, S.N. & Mazzolai, B. (2014). Structure and mechanical properties of *Octopus vulgaris* suckers. *J. R. Soc. Interface*, 11: 20130816.
- [20] Wainwright, D.K., Kleinteich, T., Kleinteich, A., Gorb, S.N. & Summers, A.P. (2013). Stick tight: suction adhesion on irregular surfaces in the northern clingfish. *Biol. Lett.*, 9: 20130234.
- [21] Tramacere, F., Beccai, L., Kuba, M., Gozzi, A., Bifone, A. & Mazzolai, B. (2013). The morphology and adhesion mechanism of *Octopus vulgaris* suckers. *PLoS One*, 8: e65074.
- [22] Wolff, J.O. & Gorb, S.N. (2016). Suction cups. In: Wolff, J.O. & Gorb, S.N. (eds.), *Attachment structures and adhesive secretions in Arachnids. Biologically-inspired systems*. Springer, Cham: 87-93.
- [23] Epstein, M.E. (1995). Evolution of locomotion in slug caterpillars (Lepidoptera: Zygaenoidea: Limacodid group). *J. Res. Lepid.*, 34: 1-13.
- [24] Kampowski, T., Eberhard, L., Gallenmüller, F., Speck, T. & Poppinga, S. (2016). Functional morphology of suction discs and attachment performance of the Mediterranean medicinal leech (*Hirudo verbana* Carena). *J. R. Soc. Interface*, 13: 20160096.
- [25] Ditsche, P. & Summers, A.P. (2019). Learning from Northern clingfish (*Gobiesox maeandricus*): bioinspired suction cups attach to rough surfaces. *Phil. Trans. R. Soc. B*, 374: 20190204.
- [26] Federle, W., Barnes, W.J.P., Baumgartner, W., Drechsler, P. & Smith, J.M. (2006). Wet but not slippery: boundary friction in tree frog adhesive toe pads. *J. R. Soc. Interface*, 3: 689-697.
- [27] Drotlef, D.M., Appel, E., Peisker, H., Dening, K., Del Campo, A., Gorb, S.N. & Barnes, W.J.P. (2015). Morphological studies of the toe pads of the rock frog, *Staurois parvus* (family Ranidae) and their relevance to the development of new biomimetically inspired reversible adhesives. *Interface Focus*, 5: 20140036.
- [28] Iturri, J., Xue, L., Kappl, M., García-Fernández, L., Barnes, W.J.P., Butt, H.-J. & Del Campo, A. (2015). Torrent frog-inspired adhesives: attachment to flooded surfaces. *Adv. Funct. Mater.*, 25: 1499-1505.
- [29] Kim, D.W., Baik, S., Min, H., Chun, S., Lee, H.J., Kim, K.H., Lee, J.Y. & Pang, C. (2019). Highly permeable skin patch with conductive hierarchical architectures inspired by Amphibians and Octopi for omnidirectionally enhanced wet adhesion. *Adv. Funct. Mater.*, 29: 1807614.
- [30] Tramacere, F., Follador, M., Pugno, N.M. & Mazzolai, B. (2015). Octopus-like suction cups: from natural to artificial solutions. *Bioinspiration Biomim.*, 10: 035004.
- [31] Follador, M., Tramacere, F. & Mazzolai, B. (2014). Dielectric elastomer actuators for octopus inspired suction cups. *Bioinspiration Biomim.*, 9: 046002.

- [32] Lee, H., Um, D.-D., Lee, Y., Lim, S., Kim, H. & Ko, H. (2016). Octopus-inspired smart adhesive pads for transfer printing of semiconducting nanomembranes. *Adv. Mater.*, 28: 7457-7465.
- [33] Sethian, J. (1998). *Fast Marching Methods and Level Set Methods for Propagating Interfaces*. Karman Institute Lecture Series, Computational Fluid Mechanics.
- [34] Varga, S., Oliveira, A., Diaconu, B. (2009). Numerical assessment of steam ejector efficiencies using CFD. *International Journal of Refrigeration* Vol. 32, 1203-1211.
- [35] Chunnanond, K., Aphornratana S. (2004). An experimental investigation of a steam ejector refrigerator: the analysis of the pressure profile along the ejector. *Applied Thermal Engineering* Vol. 24, 311–322.
- [36] Eames, I., Ablwaifa, A., Petrenko, V. (2007). Results of an experimental study of an advanced jet-pump refrigerator operating with R245fa. *Applied Thermal Engineering* Vol. 27, 2833–2840
- [37] Rogdakis, E., Alexis, G. (2000). Design and parametric investigation of an ejector in an air-conditioning system. *Applied Thermal Engineering* Vol. 20, 213–226.
- [38] Cizungu, K., Mani, A., Groll, M. (2001). Performance comparison of vapour jet refrigeration system with environment friendly working fluids. *Applied Thermal Engineering* Vol. 21, 585–598.
- [39] Eames, I., Aphornratana, S., Haider, H. (1995). A theoretical and experimental study of a small-scale steam jet refrigerator. *International Journal of Refrigeration* Vol. 18(6), 378–386.
- [40] Huang, B., Chang, J., Wang, C., Petrenko, V. (1999). A 1-D analysis of ejector performance. *International Journal of Refrigeration* Vol. 22, 354–364.
- [41] ISO 6358 (1989). *Pneumatic fluid power; components using compressible fluid; determination of flow-rate characteristics*, Beuth, Berlin.
- [42] Baehr, H., Kabelac, S. (2009). *Thermodynamik: Grundlagen und technische Anwendung*. Springer, Berlin, Heidelberg.
- [43] Monkman, G. J. (2007). *Robot grippers*. Weinheim, Chichester: Wiley-VCH