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INDUSTRY 4.0 PERSPECTIVES OF AXIAL AND RADIAL FANS IN SMART INDUSTRIAL VENTILATION: CONCEPTUAL CASE STUDIES

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ABSTRACT

Industry 4.0 envisages new functions in industrial air technology. The paper presents novel overall concepts for smart industrial ventilation, for which smart features are adopted to axial and radial flow fans. The applicability of the resultant smart fans is illustrated in two conceptual case studies. Commercial fan units were selected as candidates for the smart fans. These fan units, incorporating optional metering devices, were developed on the initiative of the manufacturers at the authors' Department. Thanks to their customized hardware, the selected fan units represent a transition in the evolution from common fans to smart fans with the following potential: comprehensive monitoring and control of gas parameters, aerodynamic performance, and noise; a priori high, controlled efficiency; a priori high, monitored resistance to harsh operating conditions; condition monitoring for the fan. Instrumentation is in the focus. Therefore, a multifunctional metering device included in the fan unit is discussed, giving a potential for measurement of flow rate, air temperature, and static pressure, even for harsh conditions. Concepts for further instrumentation built in the compact fan unit for condition monitoring, as well as sensors located inevitably out of the fan unit, are systematically discussed, together with the features of smart data processing.

Keywords:
axial flow fans, Industry 4.0, industrial air technology, industrial ventilation, radial flow fans, smart fan, smart ventilation

NOMENCLATURE

Latin letters

A	$[m^2]$	cross-section
a	$[m/s]$	speed of sound in gas
D	$[m]$	diameter of fan duct or blade tip
d	$[m]$	hub diameter of axial fan rotor
K	[-]	flowmeter calibration factor
L_W	$[dB]$	overall fan sound power level
ΔL_{Woct}	$[dB]$	relative sound power level, octave
N	[-]	blade count for fan rotor
n	$[1/s]$	fan rotor speed
P_{eff}	$[W]$	effective performance
P_{in}	$[W]$	fan drive input electric power
p	$[Pa]$	static pressure
p_a	$[Pa]$	measured annulus mean pressure
p_d	$[Pa]$	dynamic pressure
p_t	$[Pa]$	total pressure
Δp_t	$[Pa]$	total pressure rise
q_V	$[m^3/s]$	gas volume flow rate
Re	[-]	flowmeter Reynolds number
R	[-]	specific gas constant
T	$[K]$	gas temperature
T_b	$[K]$	bearing temperature
u_{tip}	$[m/s]$	rotor tip circumferential speed
v	$[m/s]$	local mean flow velocity
v_v	$[m/s]$	vibration velocity

Greek letters

η	[-]	fan efficiency based on P_{in}
η_D	[-]	efficiency of the fan drive
η_t	[-]	fan total efficiency
κ	[-]	specific heat ratio
ν	$[m^2/s]$	gas kinematic viscosity
ρ	$[kg/m^3]$	gas density

Subscripts and Superscripts

a	flowmeter annulus
P	fan pressure side
S	fan suction side

1. INTRODUCTION AND OBJECTIVES

The Industry 4.0 concept has a significant effect on the industrial processes. Energy efficiency, and reliable operation became the governing principles. The effect of Industry 4.0 is the continuous improvement of the automation into "smart factories". This necessitates the development of smart process systems [1-2]. A smart system is capable to operate without human intervention, with the aid of a computer-assisted control system and high-level sensor implementation [3]. This automated system is able to operate with high effectiveness, and is designed to avoid any failures or shutdowns. In order to assure this, the system has to be provided with an effective maintenance procedure, supported by condition monitoring [4-5]. Referring to advanced Operation & Maintenance strategies, condition monitoring is a complex predictive maintenance method, which is capable to prognosticate and diagnose a machine malfunction. This greatly reduces the maintenance time, because the planning of maintenance can be started before the work process has to be stopped. Nowadays, the condition monitoring systems operate on the basis of advanced signal processing techniques and Artificial Intelligence, thus improving the speed and reliability of decision-making [6].

As suggested by the 327/2011/EU Fan Regulation [7], fans are operated in industrial air technical and ventilation systems in such a great volume that their impact on the global economy is significant. Consequently, Industry 4.0-driven smart factories are also envisaged to incorporate systems of industrial air technology and ventilation, served by fans, in a significant portion. In line with the Industry 4.0 concept, in a smart factory equipped with industrial air technology and ventilation, "smart ventilation" systems are presumed to operate, incorporating "smart fans". This would envisage that the concepts of "smart ventilation" and "smart fan" are incorporated in the Industry 4.0 perspective, and are well-established in industrial ventilation and air technology. Nevertheless, a literature survey reveals that the concept of "smart ventilation" is nowadays mainly restricted to ventilation in residential buildings [8-9]. Furthermore, a "smart fan" is usually regarded as a room ceiling fan [10-11], or a simple home cooling fan [12-13]. The "smartness" of the aforementioned fans is often confined to features of advanced and remote personal control supervised by the user. Although the name of the SmartFAN European project may suggest a focus of smart ventilation, the project regarded the material development of the fan impeller for applications of various kind [14]. The above overview reflects that the "smart ventilation" and "smart fan" concepts are less elaborated for Industry 4.0 applications incorporating processes related to industrial air technology and ventilation.

The objective of the present paper is to provide a supplementary and comprehensive overview on the potential of smart industrial ventilation from the Industry 4.0 perspectives. To this end, novel concepts are presented for the extension of the smart ventilation and smart fan features to industrial air technology and ventilation, in accordance with the Industry 4.0 perspective. The new features of these concepts are outlined, in comparison with the traditional characteristics of systems in industry-related ventilation and air technical systems, embedding classic fans. The concept of a smart fan is feasible only with the development of an eligible system of instrumentation. This sensor system has to be able to assure the effectiveness of fan operation and the avoidance of any failures or shutdowns. Accordingly, the instrumentation to be associated with a smart fan is discussed herein. To the best knowledge of the authors, this paper is the first one providing a comprehensive discussion and synthesis on the aforementioned novel items in the present form.

2. ILLUSTRATIVE EXEMPLARY CASE STUDIES

2.1 Initial remarks

In this paper, the smart fan features are illustrated via two substantially different, representative industrial examples. One of them is a gas engine power plant, in which the delivered combustion air is utilized as input chemical component into the combustion process, i.e. it is non-recirculating. The other one is an air technical separator used for classification of multitudes of solid particles, e.g. municipal waste being processed. Here, the air serves as auxiliary medium in addition to the mass flow of the solid phase under classification, and is recirculated in the technology. These two examples are representative also in terms of the two substantially different types of the fans applied. The combustion air supply system for the gas engine power plant is typically served by *axial flow fans* in parallel connection. This is in accordance with the need for a volume flow rate of combustion air being large relative to the fan driving power, driven through system elements of relatively low pressure drop. The air technical separator is typically operated using a *radial flow fan*. Here, the flow rate is low relative to the driving power, and is converted into a concentrated, high-velocity air jet produced by a nozzle. This fact, together with the dust content of the air necessitating rough filtration casing relatively high pressure drop, results in a need of relatively high total pressure rise. Therefore, the two examples represent the possible smart application of axial as well as radial fans, being mostly widespread in industries.

The discussion on the fans is organized within the examples in the paper in an evolutionary approach. As detailed in the following, such approach means that the fans applied at various states of system development are discussed as units corresponding to the following phases of evolution: *common* fan units, without any special features → fans with selectively improved, *favourable* hardware features → fans exhibiting *eminent* features when operated as smart fans in a smart system.

A) *Common fan units* with traditional geometry and hardware, used in conventional air technical systems, are outlined first in Sections 2 2. and 2.3.

B) Options of further development of the traditional geometry and hardware within the fan units is then discussed, in correspondence to case-specific application demands, resulting in improved, *favourable fan features*. Three examples of such favourable features are as follows.

a) *A priori* high fan efficiency, by fulfilment of minimum criterion on energy efficiency.

b) In-built tool for flow rate measurement exploitable in process control.

c) *A priori* high resistance against harsh operational conditions, i.e. improved robustness, via less inclination of sensitivity to dust load.

In Section 3, commercial fan units will be selected herein with *favourable features*, as potential candidates for further development into a "smart fan" status.

C) Concepts for enhancement of the aforementioned favourable fan features to *eminent fan features* are finally outlined, via application of the smart fan concept to the candidate fans. In order to achieve *eminent fan features*, being embedded in the Industry 4.0 perspective, the previously given three examples evolve as well as interact with each other as follows.

a) Continuous monitoring and possible maximization of the fan efficiency, being *a priori* high, as contribution to rationalization of energy management for the smart factory, and providing time series of empirical data for fan condition monitoring.

b) In-built toolkit for multipurpose, comprehensive monitoring of air state variables, air technical properties, and fan input power; thus forming a basis for efficiency monitoring and advanced air technical process control in the smart factory. This necessitates instrumentation for fluid mechanics and input power.

c) Continuous fan condition monitoring e.g. on the effects of dust load, for monitoring and maintaining the resistance against harsh conditions, being *a priori* high, aiding the improvement of effectiveness of maintenance of the fan via occasional cleaning. On this basis, the periodic and relatively long, mandatorily prescribed maintenance periods can be exchanged for short, occasional, demand-based cleaning actions in a smart factory.

The implementation of the smart fan concept in point C) is organized into the following groups. 1) What "smart" hardware tools can be incorporated in an integrated, compact smart fan unit itself? 2) What "smart" hardware tools are to be installed within the system inevitably out of the fan unit? 3) What "smart" software, i.e. information technology and the incorporated theoretical as well as legislative considerations, are to supervise the aforementioned hardware in a smart ventilation system?

2.2 Gas engine power plant

The gas engine is a reciprocating engine, which transforms the chemical energy of the gaseous fuel to kinetic energy. The engines of such kind usually operate with natural gas as fuel, but there are increasing number of examples for which the fuel is biogas [15]. This power plant provides energy by cogeneration [16]. This means that not only the electrical power delivered by the driven generator is made available for use but the heat power contained by the exhaust gas and by the coolant, which would originally be wasted, may be utilized in the factory as well.

The aim of the ventilation system is supplying the gas engine with combustion air. Multiple air technical subsystems are operated in parallel connection for this purpose. Each subsystem is served by an individual fan. The structural scheme of a single air technical subsystem is shown symbolically (not to scale) in **Figure 1**, based on [16]. The fan sucks the ambient air via a rain protection grille and a segmented air duct equipped with a silencer and a preheater – the latter is for winter operation. The air is delivered into the gas engine compartment via a louvre equipped with a servomotor.

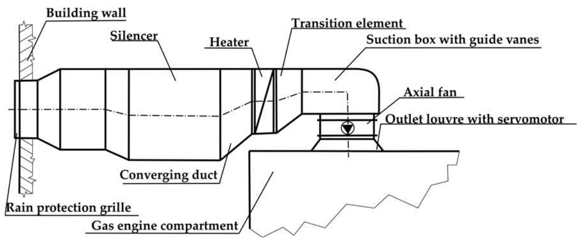

Figure 1. Structural scheme of the combustion air supply system of a gas engine power plant

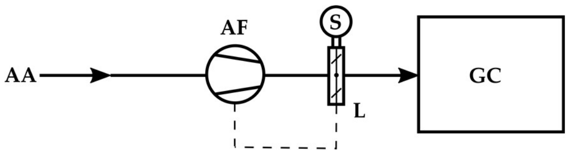

Figure 2. Operational scheme for the combustion air supply system of a gas engine power plant: a traditional layout. Notation: AA: atmospheric air, AF: axial fan, GC: gas engine compartment, L: louvre, S: servomotor.

The operational scheme of a conventional system corresponding to point A) in Subsection 2.1, incorporating a *common* fan unit, is presented in **Figure 2.** The features of the *common* fan unit, being in contrast with items a)-c) in point B) in Subsection 2.1, are as follows. a) Provided that the fan was installed prior to the date of effect of the EU Fan Regulation [7], no minimum energy efficiency requirement is set for the fan. b) Neither the fan unit itself nor the connecting system contains any flow metering devices. The flow rate-measuring as well as -controlling feature is completely missing. The louvre is fully closed when the fan is switched off. After switching on, the fan gradually reaches its full rotational speed. When the normal speed of operation is reached, the louvre is opened fully by the servomotor, following the command given by the system automatics. This action is indicated with a dashed line in Fig. 2. In this layout, the individual fan operation cannot be matched with the connecting system in terms of flow rate and efficiency demands, and changing conditions (e.g. external wind effect, or temporary lack of the gas-tightness of compartment due to door opening). c) The working condition of the fan is not monitored. The system is in lack of automatic detection of any malfunction of the fan, increasing the risk of non-forecasted failure.

2.3 Air technical separator

The air technical separator, used e.g. in processing of shredded municipal waste, is capable for separating the multitude of solid particles into various fractions, according to their difference in the ratio of mass to the aerodynamic drag [17]. This ratio is relatively large e.g. for pieces of pressed plastic bags, characterized by three-dimensional (3D) shape – hereinafter termed "heavy" fraction –, and is relatively small e.g. for pieces of sheets of plastic foil, modelled as two-dimensional (2D) in shape – hereinafter termed "light" fraction. One aim of the separator is to separate the selectively collected and shredded plastic waste into heavy – 3D – as well as light – 2D – fractions. The operation of the separator is illustrated in the structural scheme in **Figure 3**, as well as in the operational scheme in **Figure 4**. During operation, the waste is loaded onto a conveyor, which delivers it to the rotating separator drum. From below the feeding conveyor, a high-velocity air jet is blown, through a nozzle, to the upper surface of the separator drum, and is attached to the upper part of the drum via the Coanda effect. The heavy fraction is falling through the air jet, since the vertically downward motion due to the weight force dominates over the jetwise motion due to the aerodynamic drag. The heavy fraction falls to a conveyor at the bottom, and is removed (label "Heavy" in Fig. 3). The light fraction travels together with the jet, and is delivered to the other side of the drum, into the settling chamber. Here, the light fraction is settled onto a conveyor belt, and is removed from the chamber (label "Light" in Fig. 3). The injector effect due to the suction phenomenon caused by the air jet generates inward leakage flow from the surroundings via the air gaps on the casing of the separator, e.g. at the conveyor ends. This inward air leakage, indicated as AL in Fig. 4, is useful in terms of preventing the dusty air from being released to the surroundings. The air corresponding to the sum of jet flow and the inward air leakage is sucked from the settling chamber, and is recirculated to the suction port of the fan. The dominant portion of the airflow available on the pressure port of the fan is diverted by an adjustable diverting valve toward the nozzle, forming the air jet. The rest of the air is sent through a filter, and is then exhausted to the surroundings, as replacement of the inward air leakage.

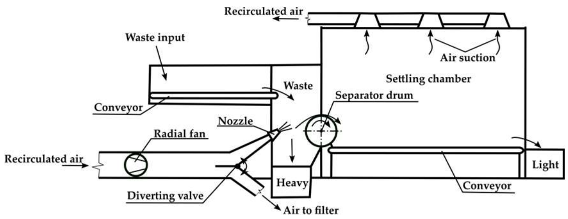

Figure 3. Structural scheme for the air handling system in an air technical separator

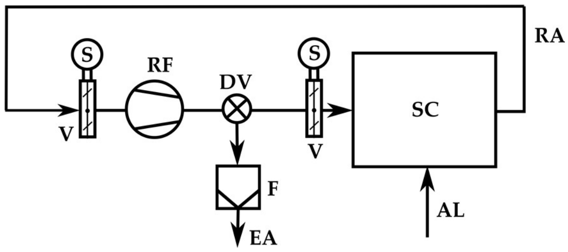

Figure 4. Operational scheme for the air handling system in an air technical separator: a traditional layout. Notation: AL: air leakage, DV: diverting valve, EA: exhaust air, F: air filter, RA: recirculated air, RF: radial fan, S: servomotor, SC: settling chamber, V: valve.

In the traditional system, the air motion is assured by a *common* radial fan with backward-curved impeller blades, corresponding to point A) in Subsection 2.1. In the case of this *common* fan unit, no special treatment has been done for fulfilment of the expectations which have been detailed in items a)-c) in point B) in Subsection 2.1. More specifically: a) No minimum energy efficiency requirement is set for the fan. b) Neither the fan unit itself nor the connecting system contains any flow metering device. c) No special treatment has been done against the optional dust load of the fan, originating from the contaminated air recirculated from the settling chamber. No condition monitoring is applied on the fan on the possible consequences of dust load, such as rotor imbalance, or performance degradation due to blade contamination.

In the traditional system, three controlling devices operate, on the basis of the details in [17]. One throttling valve, optionally operated with a servomotor, is located at the suction port of the fan, providing a general flow control on the air technical system via throttling. The diverting valve distributes the air into two directions at a ratio presumed empirically to be suitable: toward the nozzle, and toward the filter. The flow toward the nozzle can be adjusted using an additional valve, optionally operated using a servomotor. This controlling system is more complex than the one in Subsection 2.2. It is to be emphasized that the throttling method used for flow control causes additional losses in the system. Furthermore, the traditional system has no sensors implemented, neither for flow control nor for fan condition monitoring purposes.

3. POTENTIAL CANDIDATES FOR FURTHER DEVELOPMENT INTO A SMART FAN STATUS

As further development of the examples in Subsections 2.2 and 2.3 incorporating *common* fan units, being in line with point B) in Subsection 2.1, commercially available fans and their optional accessories are discussed herein, in possession of *favourable fan features*, thus being potential candidates for further development into a smart fan status. Specifying these commercial products herein is not to be considered as commercialism; i.e. the commercial products taken below as examples are not to be regarded as exhaustively preferred and sole candidates for the smart fan solutions outlined herein. However, they demonstrate the industrial and commercial feasibility and cost-effectiveness of the smart fan concept discussed herein, with details being well-known for the present authors, because the authors' Department played a key role in their research and development.

3.1 Axial flow fan

In relationship with the case study on the gas engine power plant, one possible candidate of *favourable fan features* to be further developed into a smart industrial axial fan status is a member of the VHA ducted fan family [18] manufactured by Hungaro-Ventilátor Kft. (Hungaro-Ventilátor Ltd.). This fan family and its accessories have been developed by the firm in collaboration with the authors' Department. Further details on the fan family are given in [19-20]. This fan family provides examples for the *favourable* features as fulfilment of criteria in examples a) and b) within point B) in Subsection 2.1 as follows.

a) Thanks to its careful aerodynamic design carried out at the Department, the fan family meets the prescribed efficiency criterion fixed in the Fan Regulation [7]. Such efficiency requirement is fulfilled even by applying an easy-to-manufacture geometry, i.e. circular-arc plate blading, providing cost-effectiveness, and thus, competitiveness on the market.

b) The members of the fan family can be equipped with a commercially available in-line volume flow rate metering device, developed for the company by the Department, being fixed upstream of the axial fan with minimum space requirement, and thus, being integrated into the compact axial fan unit itself. Therefore, a compact fan-and-measurement unit can be made available, providing flow rate data for process control, and also enabling a potential for smart features which are detailed later in this paper.

Hungaro-Ventilátor Kft. equips its axial fans with the compact in-duct inlet metering device upon demand by the customers. The front axial view and the longitudinal section of the metering device are outlined in **Figures 5 and 6**. From operational point of view, this instrument acts like a giant Pitot-static (Prandtl-) probe, conf. [21]. Accordingly, the volume flow rate is deduced from measuring a single mean velocity measured by the flowmeter, being representative for the rotor annulus (i.e. the annular region embedding the rotor blades), and multiplying it by the annulus area. The flanged flowmeter is to be coaxially attached directly to the upstream flange of the fan casing. The upstream installation of the flowmeter is to exclude the flow irregularities caused by the fan from the measurement (e.g. swirling outflow, wake of the hub incorporating the driving motor). The central part of the device is the nose. The steady nose acts practically as the protrusion of the rotating hub of the impeller, being identical in diameter, and having only a small gap in between. The rear wall of the nose is closed. Therefore, the nose embeds a stagnant flow zone, and therefore, enables the measurement of inlet total pressure p_t by means of a Pitot probe immersed radially into the nose from outside. The flanged outer part, labelled as duct extension in the figures, is actually an upstream elongation of the fan casing. It supports the nose coaxially with use of radially aligned flat plates, acting also as inlet guide vanes against accidental inlet flow distortions. Inside the nose, wall pressure taps are executed and connected by an internal round piping. By such means, the averaged pressure over the outer surface of the nose – wetted by the annular flow – is tapped, and is led out of the flowmeter using a pressure transducer pipe. The internal surface of the duct extension, exposed to the annular flow, is also equipped with wall taps, connected by an external round piping. The pressure provided by the internal and external round pipes is averaged via a T-connector, thus providing a spatially averaged annulus mean pressure p_a, being an approximation of the mean static pressure valid for the annular flow.

The flowmeter has thoroughly been designed by the Department for fulfilment of demands of compactness, robustness, operational safety, and simple, easy-to-manufacture flowmeter geometry, thus guaranteeing cost-effective production and market competitiveness. Thanks to the large extension of the stagnant fluid region inside the nose, p_t can be measured in a robust and accurate manner, i.e. insensitively to accidental inlet flow distortions. The internal Pitot probe can be manufactured with relatively large internal diameter. This fact, together with the large "stagnation tap" represented by the nose itself, guarantees that the measurement of p_t can be carried out also in contaminated (e.g. dusty) flow with moderate risk of clogging. The relatively large number of wall taps located over the circumference of both the nose and the duct extension guarantees a robust and accurate determination of p_a, even for inlet ducts with increased flow distortions – e.g. an elbow or throttle located close upstream –, and even for harsh operating conditions such as gas flow laden with solid contaminants. In addition, the flowmeter acts as a flow straightener from the perspective of arrangement of inflow to the rotor blades, being anyway of increased non-uniformity due to the upstream flow distortions. The measurement experiences of the company justify the robustness of this flowmeter technology. By the aforementioned means, this flowmeter technology is competitive with other techniques available commercially for inbuilt flow rate measurements for fans, e.g. [22-23].

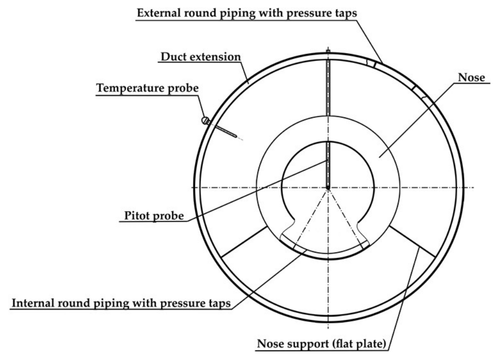

Figure 5. Compact inlet metering device for ducted axial fan units: front axial view

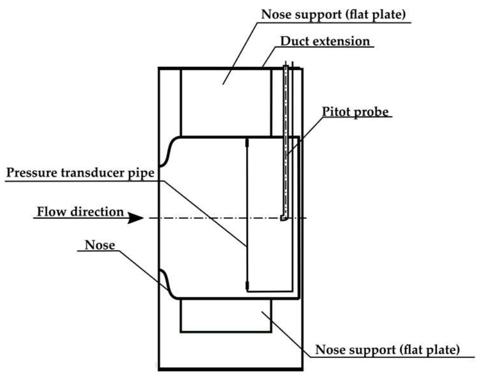

Figure 6. Compact inlet metering device for ducted axial fan units: longitudinal section

With use of the measurement-based p_t and p_a pressure data, provided by the flowmeter as a giant Pitot-static probe, the flow rate is calculated as follows. Taking the idealistic assumption that p_a represents the mean static pressure in the annulus, the dynamic pressure p_d is derived as follows.

$$p_\mathrm{d} = p_\mathrm{t} - p_\mathrm{a} \tag{1}$$

The mean velocity in the annulus is calculated using the following equation:

$$v_\mathrm{a} = \sqrt{\left(\frac{2 \cdot p_\mathrm{d}}{\rho}\right)} \tag{2}$$

The need for accuracy of the measurement, being influenced by the knowledge of the gas density ρ, is dependent on the demand by the customer. For a brief estimation of the flow rate, the standard air technological air density of ρ = 1.20 kg/m^3 can be used in Eq. (2). In more demanding applications, ρ is to be determined from measurements, as discussed in Subsections 4.1 and 4.2.

The annulus cross-section is obtained as follows:

$$A_\mathrm{a} = \frac{(D^2 - d^2)}{4} \cdot \pi \tag{3}$$

In the idealistic approach described above, the volume rate would be obtained as product of the mean velocity and the annulus cross-section. In order to consider the realistic effects, the idealistically obtained volume flow rate is to be multiplied by a calibration factor *K*:

$$q_\mathrm{V} = K \cdot A_\mathrm{a} \cdot \sqrt{\left(\frac{2 \cdot p_\mathrm{d}}{\rho}\right)} \tag{4}$$

In order to obtain *K*, the flowmeters are factory-calibrated, with use of standardized fan facilities [21], over Reynolds number intervals representing the operational range for the fans. The calibration diagrams are case-specific for given types of flowmeter-fan assemblies. The Reynolds number is calculated using the mean velocity in Eq. (2) as follows:

$$Re = \frac{v_\mathrm{a} \cdot D}{\nu} \tag{5}$$

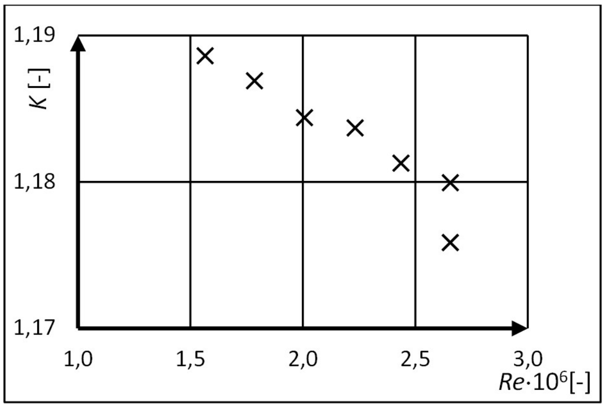

Figure 7. Calibration diagram for the compact inlet metering device: an example

Figure 7 shows an example for the calibration diagram *K*(*Re*) for an operational range being representative for a given fan application. The figure indicates that the relative variance of *K*, with respect to the mean value, is significantly below the ± 2 % maximum allowable uncertainty of standardized [21] fan flow rate measurements. Therefore, the developed flowmeter can suitably be applied with a practically constant calibration factor, thus aiding a straightforward evaluation method.

3.2 Radial flow fan

In connection with the case study on the air technical separator, one possible fan exhibiting *favourable features*, and thus being a candidate to be further developed into a smart industrial radial fan status, is a member of the new LDL radial fan family [24]. The manufacturer is Szellőző Művek Kft. (Ventilation Works Ltd.). This fan family has been designed, developed and experimentally tested by the authors' Department for the company. A detailed description is given on the fan family in [25], and therefore, only a brief summary is given here. This fan family provides examples for the *favourable* features as follows, in fulfilment of criteria in examples a) and c) within point B) in Subsection 2.1.

A classic air technical separator system is equipped with a traditional fan with backward-leaned, curved – i.e. cambered plate – impeller blades. However, in the separator case study presented herein, the inbuilt radial fan delivers air with apparent dust load. The traditionally curved sheet metal blades exhibit an increased inclination to be contaminated. In order to moderate blade contamination due to the dust load, the backward-leaned rotor blades have been designed as straight, planar sheet metal blades, instead of the traditional curved blade geometry. Despite the simplified blade geometry, the fitting and assembly of the inlet cone, the rotor, and the scroll casing has been developed by such means that a reasonably high efficiency has been reached, fulfilling the Fan Regulation [7].

The straight blade design enables an increased resistance against abrasion and cake formation – „self-cleaning" geometry –, whereas the entire machine exhibits a reasonably high efficiency. On this basis, the criteria in examples of both c) and a) within point B) in Subsection 2.1 are fulfilled.

4. OPTIONS FOR SMART FAN FEATURES

In what follows, details a)-c) within point C) in Subsection 2.1 are discussed, via the examples of the axial and radial fan units presented in Subsections 3.1 and 3.2. Namely, it will be examined how the *features* of these fan units, being *a priori favourable*, can be further developed to *eminent fan features* via the application of the smart fan concept to these candidate fans, in the Industry 4.0 perspective. In accordance with items a)-c) within point C) in Subsection 2.1, the present section is organized into the following topics: efficiency monitoring and control; instrumentation for fluid mechanics and input power; condition monitoring. As written at the end of Subsection 2.1, these topics are discussed in terms of 1) hardware built compactly in the fan unit; 2) hardware installed in the system out of the fan unit; 3) software, involving theoretical as well as legislative and reference considerations – such as regulation, standards, graphs of standardized certification measurements on fans and driving motors –, and solutions in information technology.

4.1 Efficiency monitoring and control

The effective aerodynamic performance P_{eff} of the fan is obtained as product of volume flow rate q_{V} and total pressure rise Δp_{t}:

$$P_{\mathrm{eff}} = q_{\mathrm{v}} \cdot \Delta p_{\mathrm{t}} \qquad (6)$$

In the case of the ducted fans playing role in the two exemplary case studies, the total pressure rise Δp_{t} is obtained as the difference between the total pressures valid for the fan pressure and suction sides:

$$\Delta p_{\mathrm{t}} = p_{\mathrm{tP}} - p_{\mathrm{tS}} \qquad (7)$$

At either on the pressure side or on the suction side, the total pressure is obtained as follows:

$$p_{\mathrm{t}} = p + \rho \cdot \frac{v^2}{2} \qquad (8)$$

The air density is obtained from the ideal gas equation:

$$\rho = \frac{p}{R \cdot T} \qquad (9)$$

In accordance with the Fan Regulation [6], the input power P_{in} to be considered herein for efficiency calculation is the input electrical power to the fan driving motor. On this basis, the fan efficiency η is obtained using the following formula:

$$\eta = \frac{P_{\mathrm{eff}}}{P_{\mathrm{in}}} \qquad (10)$$

For continuous monitoring of fan efficiency on the basis of Eqs. (6) to (10), the following quantities are to be measured. The discussion follows the sequence of the equations, with additional comments as appropriate.

Eq. (6): q_{V} is to be measured. If the possible measurement location is restricted to the vicinity of the fan, a section upstream of the fan is recommended, in order to avoid the flow irregularities caused by the fan on the measurement.

Eq. (7): p_{tS} and p_{tP} are to be determined. One possibility is the direct measurement of the local total pressure p_{t}.

Eq. (8): Another possibility is obtainment of the total pressure as sum of locally measured static pressure p and locally calculated dynamic pressure. The latter can be obtained from the measured q_{V} with knowledge of the local cross-sectional area (obtaining v) and the density ρ. In the duct in the vicinity of the fan, usually only the upstream static pressure p_{S} can be measured correctly, because of the irregularities caused by the fan on the downstream flow field.

Eq. (9): For determination of the density ρ, the temperature T is to be measured at a location where the local static pressure p is known. Since the assumption of incompressibility is a reasonable approximation in the case of fans [26], the density determined by such means can be taken as a single representative value for fan operation.

Eq. (10): The electric power P_{in} input to the driving motor is to be measured.

The above described workflow, resulting in the *data package for efficiency monitoring and control*, is summarized as follows, in the sequence of Eqs. (6) to (10).

- Measurement-based quantities: q_V, p_t and/or p at both the S and P locations, T at one location where p is obtained from measurement, P_{in}.
- Derived quantities: Δp_t, P_{eff}, ρ, η.

The continuous monitoring of the elements of the *data package for efficiency monitoring and control* offers the following benefits for Industry 4.0 functions in smart ventilation.

- P_{in} serves as input data to the overall energy management of the smart factory, in terms of energy consumption as well as loading of the subsystem supplying electric energy to the fan driving motor; e.g. monitoring of electric current input to the motor in relationship of the electrical fuse.
- η indicates the rationality of energy use in fan operation, and provides input data to system control for a possible, smart improvement of energy efficiency for system operation. The evaluation of measurement-based η is to be carried out on the following, *multilevel basis*. a) As a first phase in judgment of η, it is to be compared with the efficiency criterion dictated by the Fan Regulation [7] for the best efficiency point of the fan. b) As a second phase in evaluation of η, it is to be compared with data of the $\eta(q_V)$ fan efficiency curve known from the standardized certification measurements [21] to be provided by the fan manufacturer/vendor company, for given operating conditions of ρ and n. c) As a third phase, the system operator must have the complete smart air technical system – equipped with all components and instrumentation – to carry out *reference "self-measurements"*, over the entire controllable operational range, *prior to* the actual industrial utilization of the system. Such *self-measurements* provide associated reference data packages on q_V, Δp_t, and η over the entire controllable operating range. These reference data are to be compared with time series of such data obtained later, during system operation, for condition monitoring purposes. On the above multilevel basis, the possibility for modification of the actual operational point of the fan for improvement of the energy efficiency and/or moderation of energy consumption of the system, by means of appropriate control, can be overviewed. For smart control of the electric input power and the efficiency, throttle-based control elements, such as the ones outlined in Fig. 4, tend to be partly or fully replaced with speed control of the fan, whenever possible, for more energy-efficient operation.
- q_V, p_t and/or p at the S and P locations, and T are characteristics not only for the fan but also for the connected system. As such, they can be used in development of advanced flow control, thus enabling a flexible fitting of the fan to the connected system, in accordance with the user demand.
- A two-level comparison can be carried out as follows. a) With knowledge of q_V, the actual operation point can be identified on the fan characteristic curve $\Delta p_t(q_V)$ and on the efficiency curve $\eta(q_V)$ originated from the standardized certification measurements [21] provided by the fan manufacturer/vendor. On this basis, certified reference measurement data are to be made available for both Δp_t and η. The actual measurement-based Δp_t and η quantities are to be compared to the aforementioned certified reference data. b) Another type of referencing is made possible on the basis of the aforementioned *reference self-measurements*. A deterioration of the actually measured Δp_t and/or η quantities relative to the reference data indicates fan degradation. Therefore, the dataset of q_V, Δp_t and η can be utilized in fan condition monitoring, discussed in Subsection 4.3.

It is to be generally emphasized that in comparison of the actual measurement-based quantities with references – such as [7], or certified [21] $\Delta p_t(q_V)$ and $\eta(q_V)$ data –, the uncertainty of the actual measurements as well as of the experimental references, the tolerance grades [27] stated for the fan, and the related allowable variance in the quantities, are to be considered.

For conversion of the $\Delta p_t(q_V)$ and $\eta(q_V)$ graphs to the actual operating conditions via the fan similarity laws [26], ρ and n is to be known. Since n is generally not expected to be measured herein, additional information is necessary on the fan drive for determination of the rotor speed n. For example, for fans driven directly by asynchronous electric motors, the $P_{in}(n)$ characteristic curve of the motor, being made available by the motor manufacturer via certification measurements, serves as basis for determination of n with knowledge of P_{in} measured.

4.2 Instrumentation for fluid mechanics and input electric power

The fluid mechanics instrumentation for smart ventilation features outlined above is illustrated via the exemplary case studies in Subsections 2.2 and

2.3. Referring to Fig. 1, a smart axial fan serving for the gas engine air supply system is equipped with speed control. The louvre is fully open when the fan operates. The compact inlet metering device detailed in Subsection 3.1 enables measurements upstream of the fan. Referring to Fig. 1, the integration of the metering device and the fan into a compact fan unit makes possible the installation of the fan unit in the confined vertical space between the suction box and the ceiling of the gas engine compartment. This appears to be the sole adequate solution for q_V measurements in this particular system. The robust metering device can operate well despite the flow distortion caused by the suction box located close upstream of the meter. As already indicated in Fig. 5, the meter, serving originally for measuring q_V, can be supplemented with a temperature probe, following the guidelines in [21] for temperature measurements as a first approach. By such means, the compact inlet metering device can be further developed into a multifunctional meter providing the following data, conf. the comments in Subsection 4.1: p_{tS}, T, q_V, and p_S – the latter is calculated from Eq. (8) with consideration of ρ (Eq. 9) and the inlet dynamic pressure based on the mean inlet velocity obtained from q_V. All of the locally measured pressures discussed herein are taken relative to a fixed reference (gauge) pressure in the system, e.g. ambient atmospheric pressure.

For obtaining Δp_t, p_{tP} or p_P is also to be determined; the two latter are related via Eq. (8). Due to flow irregularities caused by the fan on the downstream flow field, and due to the presence of the outlet louvre, the pressure close downstream of the fan cannot be measured appropriately. Therefore, it is inevitable to install a p_P sensor farther away from the fan, i.e. in the nearly motionless air field in the gas engine compartment. Neglecting the loss of the fully open outlet louvre, the measured p_P value is considered to be valid as ambient static pressure in the jet close downstream of the fan. With knowledge of q_V and the fan outlet cross-section, the obtained mean outlet velocity makes possible the calculation of p_{tP} via Eq. (8).

Referring to Fig. 3 for the smart radial fan serving for the air technical separator, the direct application of the above described compact multifunctional inlet metering device – customized to the axial fan rotor annulus – is irrelevant. Instead, traditional methods are to be used farther away upstream and downstream of the fan for determining q_V, p_t, and/or p at both the S and P locations, and T at one location of static pressure measurement. The apparent dust load in the transported air is to be considered in design of the instrumentation. The standard [21] serves with guidelines regarding the location, installation and execution of these measurements. One possibility is the following installation of measurements, in analogy to the gas engine air supply measurements discussed above. a) Measurement of p_{tS} or p_S, T, and fan q_V in the straight duct of recirculated air near the suction port of the fan. b) Measurement of p_P close downstream of the fan, after a straightener inserted in the pressure-side duct. c) Measurement of flow rate from the diverting valve toward the filter, for calculation the flow rate in the nozzle.

In order to measure P_{in}, the electric motor driving of the given fan is to be equipped with an input electric power measuring method. For this purpose, [21] recommends the two Watt-meter measuring method provided that the fan is driven by a three-phase electric motor.

4.3. Fluid mechanics-based condition monitoring

As was described in Subsection 4.1, the measurement-based actual q_V, Δp_t and η data are to be compared with reference data on a *multilevel basis*. This comparison serves for fluid mechanics-based fan condition monitoring. The discrepancy detected in such comparison, and / or the temporal trend of deterioration recognized in the time series of Δp_t and / or η at a fixed q_V indicates a degradation of the fan, e.g. due to abrasion, or to contamination caused by the dust load. Condition monitoring and recognition of degradation for industrial turbomachinery such as compressors, gas turbines and gas turbine systems is established in the literature [28-30]. This methodology is to be adapted to industrial fans with appropriate modifications. Since the present literature lacks in directly available guidelines for trend analysis and monitoring the degradation in fans, the adaption of the available knowledge [28-30] to fans is subject of future research.

The fluid mechanics-based condition monitoring methodology can be supplemented with further features, thus establishing an extended toolkit for condition monitoring of smart fans. These features, discussed in the following section, are as follows:

- Noise monitoring and control
- Vibration monitoring
- Bearing temperature monitoring

5. EXTENDED TOOLKIT FOR CONDITION MONITORING

5.1 Noise monitoring and control

Incorporating an extended dataset on various types of industrial fans, guideline [31] can serve as an experimental reference database for noise monitoring of fans. Based on the work by Regenscheit (discussed in [26]), as well as presenting measurement data, guideline [31] provides semi-empirical formulae for estimation of the L_W level of sound power – in both A-weighted and linear form upon need – emitted by the normally operated fan into the outlet duct. Correlations for estimation of level of sound power radiated toward the inlet duct, or emitted at a free outlet, are also available in [31]. The necessary Δp_t and q_V data inputs to these formulae are available from the *data package for efficiency monitoring and control* discussed in Subsection 4.1. Further necessary data inputs are the rotor tip circumferential speed u_{tip}; the speed of sound a; and the total efficiency η_t of the fan in itself, i.e. disregarding the losses of the fan drive. u_{tip} can be calculated with knowledge of the rotor speed n determined as discussed at the end of Subsection 4.1 a can be determined with use of the measured temperature T as follows: a = $(\kappa \cdot R \cdot T)^{0,5}$. η_t is to be calculated using Eq. (11), i.e. the rotor shaft input power is to be considered instead of P_{in}. The η_D efficiency of the fan drive, representing the ratio between the rotor shaft input power and P_{in}, can be determined e.g. using the $\eta_D(n)$ characteristic curve of the driving motor, being made available by the motor manufacturer via certification measurements, conf. the end of Subsection 4.1.

$$\eta_t = \frac{\eta}{\eta_D} \tag{11}$$

Guideline [31] provides empirical formulae also for the spectral distribution of fan noise, in the form of ΔL_{Woct} relative sound power level in octave bands, as function of u_{tip}. According to [31], such spectral distribution is to be corrected for consideration of rotational noise, by adding an empirical value to ΔL_{Woct} for the octave band containing the blade passing frequency $N \cdot n$. By such means, [31] potentially represents a theoretical relationship between the noise and vibration monitoring methodologies – the latter is discussed in Subsection 5.2 –, since the peaks at $N \cdot n$ and at its overtones may appear also in the spectral distribution of vibration, via rotor-stator interaction effects. Furthermore, since guideline [31] establishes correlations between the aerodynamic power loss and the fan noise, it also represents a theoretical relationship between the monitoring/control packages of efficiency and noise.

By means of a single microphone / multiple microphones installed appropriately in the vicinity of the fan, representative sound pressure data can be acquired on the actual operation of the fan. Such sound pressure data may *implicitly indicate* the sound power emitted by the fan, and can thus be utilized for noise-based fan condition monitoring purposes. In this paper, when system measurement data on L_W and ΔL_{Woct} are referred to, they are to be considered as locally measured sound pressure data representing *implicitly* the aforementioned quantities. Such acoustic measurements can incorporate both overall sound pressure levels and the spectral distributions of noise. Following the methodology outlined for η in Subsection 4.1, the evaluation of such acoustic measurements can be carried out on a *multilevel basis*, in comparison with the following reference data. In this comparison, the uncertainty of the actual measurements as well as of the experimental references, reported e.g in [31], are to be considered. a) L_W and ΔL_{Woct} data based on [31]. b) L_W and ΔL_{Woct} data provided by the fan manufacturer/vendor company on the basis of standardized factory measurements. c) Acoustic *reference self-measurements* on the system over the entire controllable operational range.

Taking [31] as basis for comparison, reference data of L_W and ΔL_{Woct} are to be obtained using operational and geometrical data of the fan in point. The actually measured acoustic data are to be exposed to Fast Fourier Transformation (FFT) and to be represented in logarithmic scaling. The relevant frequency range is to be determined from the dimensionless Strouhal number range specified in [31] for the octave-band spectrum of the given fan type, using n as parameter. In order to make the measurement-based sound pressure spectrum comparable with the reference ΔL_{Woct} distribution derived from [31], octave-band averaging is to be carried out on the measured dataset. Significant discrepancies between the spectral trends of measured and reference ΔL_{Woct} data are to be suspected as signatures of extraordinary fan operation, e.g. extreme throttling, or fan degradation. Narrowband signatures of detected noise, peaking out of the octave-band averaged spectrum, such as the rotational noise at the blade passing frequency $N \cdot n$, are to be monitored and interpreted in a distinct manner, with special attention. FFT on algorithmically selected shorter-term time series of acoustic data provides a means for discovery of extraordinary fan phenomena, such as vibration of a loose internal machine element, e.g. a piece of plate guide vane, generating occasional noise.

Temporally evolving discrepancies in the trends between the actually measured acoustic data and the aforementioned a)-c) references can be considered as precursors of deterioration of fan conditions. Microphone installation, data acquisition and processing, establishment of correlations between various types of fan degradation and their acoustic signatures, and incorporation of acoustics-based recognition of fan degradation in smart ventilation, are subjects of further research.

It is to be emphasized that the actual air technical system and its environment may have a significant impact on the acoustic measurements. From this point of view, the on-site *reference self-measurements* – incorporating the acoustic features of the system and the site – are of especial importance in evaluation of the noise measured during the actual utilization of the system. As an approximation for considering the acoustic features of the system connected to the fan, guidelines [32-33] can be considered.

In order to moderate / avoid the acoustic impact of the connected ductwork on the observation of fan noise, noise monitoring can be carried out via sections of acoustically transparent duct [34] developed at the Department. The application of acoustically transparent ducts to industrial ventilation systems, and evaluation of fan noise data for condition monitoring purposes is a topic of future research.

The continuous monitoring of noise serves as basis also for the moderation of noise via an appropriate flow control of the system. However, attention is drawn that the primary aim of system control is fulfilment of the functionality of the air technical system, i.e. realization of the necessary q_V at favourable operating conditions, e.g. moderate aerodynamic loss. The Regenscheit formula in [31] provides a theoretical basis for noise reduction via reducing both the aerodynamic power loss of the fan and u_{tip}, i.e. via appropriately tuning q_V, Δp_t, η_t and n by system control. Such noise control can be considered as an important action in fulfilment of Environmental, Health, and Safety (EHS) measures serving for the personnel and the environment of the smart factory.

For modern ventilation systems, a recent trend is to exchange the classic metal ductwork with textile air duct elements [35], as far as the particular industrial application allows for that. Textile elements are available for straight duct sections, perforated air distributors, elbows, T-junctions, and throttles. Compared to classic ductwork, among others, the following benefits of textile air duct elements represent possible competitive advantages in a smart ventilation system. Silent textile ductwork, i.e. reduced impact on noise generation, thus making possible a more effective noise monitoring and control. Energy-efficient air transport and distribution. Quick and easy processes of removal, cleaning in washing machine, and re-installation of the textile duct elements, as part of the demand-based, effective, smart maintenance actions.

5.2 Vibration monitoring

The aforementioned tools for condition monitoring can effectively be supplemented with the means of vibration monitoring. Periodically executed non-continuous monitoring [36] of vibration is a well-established technique in diagnostics of rotating machinery. In the case of a smart fan, continuous monitoring of vibration and the associated trend analysis [36] can be a means for early recognition of risk of malfunction.

Every rotating machine has a normal level of vibration. If this level increases, it forecasts a sort of malfunction, leading to damage [36]. The increased level of vibration could originate from mechanical issues – e.g. bearing degradation, shaft imbalance, rotor imbalance due to abrasion or contaminant deposit, or resonance –, and from aerodynamic phenomena, e.g. extraordinary operational states incorporating extreme throttling, rotating stall, or surge.

The vibration can be characterized using its displacement, velocity v_v, or acceleration. The type of vibration sensors is to be selected on the basis of the layout of the fan. In the exemplary case study of Subsection 3.1, the axial fan is directly driven by the electric motor, i.e. the fan impeller is attached to the shaft of the motor. Furthermore, the motor is equipped with roll-bearings. For such kind of bearings, the recommended [37] sensor type is the accelerometer. Modern sensors of this kind operate with an integrator, which can convert the vibration acceleration to velocity v_v or displacement upon need. Signal processing techniques such as FFT are available for precise diagnosis. The placement of the vibration transducers is recommended by the standard [36]. In principle, three sensors are to be placed to each bearing house, for the axial, horizontal, and vertical directions of vibration. Reasonable compromises are to be made in installation of the sensors upon the accessibility of the bearing houses [36] e.g. in the case of electric motors with embedded bearings.

In order to realize a methodology fitting the best to the one outlined for η in Subsection 4.1, the evaluation of vibration measurements can be carried out on a *multilevel basis*, in comparison with the following reference data, considering the experimental uncertainties. a) Displacement or v_V data based e.g. on [36], specifying empirical threshold values for vibration displacement or velocity root-mean-square (RMS), for which unlimited long-term operation is allowable; short-term operation is allowable; and vibration causes damage. b) Upon availability, factory-measured v_V data provided by the fan manufacturer/vendor company. c) Vibration *reference self-measurements* on the fan over the entire controllable operational range.

In order to retrieve valuable information from the acquired signals about the condition of the machine, signal processing techniques are to be carried out. Firstly, the analogous measurement signal is to be converted into binary digital data for computer processing. For this purpose, an A/D converter is applied. This processor samples the data at regular time intervals [37]. The sampling time interval is usually expressed by its reciprocal value, i.e. the sampling frequency. The required minimum of sampling frequency is defined by the Nyquist-theorem, stating that the sampling frequency needs to be at least twice as much as that of the highest-frequency component of interest in the sampled signal [38]. In the case of an insufficiently high sampling frequency, the converted signal is affected, i.e. aliasing occurs [38]. The obtained digital signal is in the time domain. As such, it provides a means for monitoring how the vibration level varies in time. The standards usually refer to the RMS of the monitored vibration amplitude level [36]. Tracking of the vibration level through the time gives the smart fan an effective tool to alarm a malfunction well in advance. For improving the diagnostics capability, time-domain tracking is combined with transforming the signal into the frequency domain. The applied method is termed Discrete Fourier Transform (DFT). A less computation-demanding algorithm is FFT [37, 38]. In the frequency domain, the type of malfunction can be diagnosed. The main concept is that various kinds of malfunctions show signatures of changed amplitudes at various frequencies, which makes them distinguishable [37]. The signal is measured in a finite temporal interval, which may cause "leakage", because usually the first and the last sampled data are not the same. In order to avoid such anomaly, the signal is to be provided with a window function. The windowing method makes the first and the last data of the sampled signal zero. By such means, a continuous signal is obtained [37, 38].

The trend analysis in vibration monitoring for smart fans, as well as its relations with the other smart condition monitoring features from a smart data processing point of view, is subject of future research.

5.3 Bearing temperature monitoring

Temperature measurement within the fan driving electric motor is routine even in traditional layouts for overheat protection, and therefore, is not discussed herein. This subsection regards temperature measurements on the bearings, being strategically important elements in rotating machinery. The forthcoming failure of the bearings is probably associated with increased friction, leading to increased heat generation. Therefore, measuring T_b is a sensible means for monitoring the condition of the bearings [39], also influenced by the particular circumstances of lubrication. A preset limit of T_b must not be exceeded in operation. The methodologies of vibration, noise, and bearing temperature monitoring can be linked in a smart manner, in the view that the signatures of upcoming bearing failure probably appear as precursors in each of the noise and vibration spectra as well as in the T_b registrations.

Temperature monitoring is feasible with one sensor per bearing [39]. The default sensor type is the resistance-based temperature probe. For certain motor layouts, thermocouple is an alternative [39]. The probes are to be built inside the bearing houses, near the bearings.

There is no standard or any other generalised legislative reference for judging the measured T_b data in monitoring. This topic, and its relations within the overall toolkit of smart fan monitoring, is subject of further research.

6. AN OVERVIEW OF THE ESTABLISHED SMART FAN CONCEPT

Figure 8 presents a flowchart making a connection between the all-round pool of measured quantities – presented in the uppermost row –, the quantities derived from the measured data – organized into multiple levels below –, and their input into the all-round set of possible smart functions – lowermost row. The figure depicts a rich interaction and multiple data exploitation within the entire set of measured and processed data as well as the smart functions. In addition to the smart functions indicated in the figure, the capabilities of the smart ventilation system also enable advanced features of flow control.

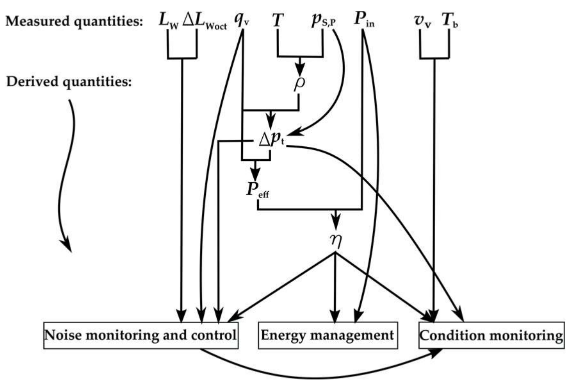

Figure 8. Flowchart between the measured quantities and the all-round set of possible smart

Figures 9 and 10 show the operational schemes for the smart layouts of the systems in the two exemplary case studies, being in accordance with the former discussion. Making a comparison to the operational schemes for the traditional layouts, i.e. comparing Fig. 9 to Fig. 2, and Fig. 10 to Fig. 4, the extensive implementation of sensors in the smart systems is conspicuous. A recent trend is to apply low-cost "Do-It-Yourself" (DIY) sensors, e.g. [40]. DIY pressure, temperature, power, noise, and vibration sensors may provide a cost-effective solution even in the case of multiple instrumentation, whereas they may be sufficiently reliable for detecting the quantities and their temporal trends for control and monitoring purposes in a smart system.

Associated time series of the measured quantities are to be acquired during the normal use of the air technical system, and the set of derived quantities are to be provided. For and control and condition monitoring purposes, these quantities are to be compared to reference data. The former discussion leads to the following generalization of *multilevel basis* for referencing for the various tools of fan condition monitoring, upon availability: a) Legislative, standardized, and guideline references [7, 31, 36]. b) Certified factory measurements on fans and drives. c) *Reference self-measurements*. The differences between the actual and reference data, and the temporal trend of these differences are to be analysed, and precursors of deterioration of fan conditions are to be recognised. Temporal predictions are to be made for various items of fan degradation, as an aid to demand-based maintenance actions.

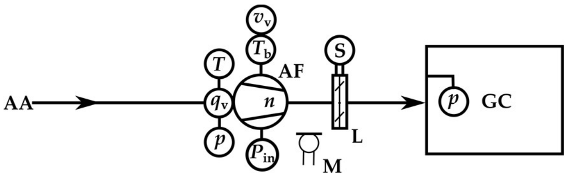

Figure 9. Operational scheme for the combustion air supply system of a gas engine power plant: a smart layout. Notation: i) See the caption of Fig. 2. ii) n: fan speed control. iii) M: microphone for noise monitoring. iv) Symbols in circles: instrumentation for measuring quantities from the Nomenclature.

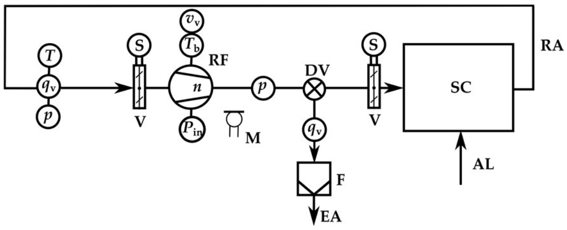

Figure 10. Operational scheme for the air handling system in an air technical separator: a smart layout. Notation: See the captions of Figs. 4 and 9.

A complex and comprehensive evaluation and trend analysis of the entire dataset in Fig. 8, being a subject of data science, provides a plentiful means for multipurpose control and condition monitoring. The expected physical phenomena, the signatures and precursors of which are "hidden" in the data, are supposed to be linked to multiple data in Fig. 8. Such redundancy of information provides a means for efficient discovery and multi-perspective confirmation of the presumed phenomena, and refinements in fan diagnosis – i.e. making distinctions between various deterioration mechanisms –, via analysing the correlations between the time series of various data. Some examples for such redundancy of information in the proposed "smart" dataset are as follows. First, the presumed physical phenomenon in point is specified. Then, followed by a "$\rightarrow$" sign, the quantities presumably modified due to the phenomenon are listed, with additional comments in brackets as appropriate.

- Rotor blade abrasion or contaminant deposit $\rightarrow$ Δp_t, η (at a given q_V, presumably due to modification in blade section lift and/or drag [26]); L_W, ΔL_{Woct} (presumably via modification of aerodynamic power loss [31]); v_v spectrum (via rotor imbalance, presumably at frequencies related to n and its overtones).
- Rotor blade and/or shaft deformation $\rightarrow$ L_W, ΔL_{Woct}; v_v spectrum.
- Degradation of fan drive (e.g. V-belt drive) $\rightarrow$ Δp_t, η (presumably via the deterioration of P_{eff}); L_W, ΔL_{Woct}; v_v spectrum.
- Bearing degradation $\rightarrow$ L_W, ΔL_{Woct}; v_v spectrum; T_b.

The trends outlined above are to be discovered in a synchronized manner, by means of proper algorithms. For improving the effectiveness of the smart system for the future, the system is to learn the experiences gathered in the past on fan condition monitoring, with also incorporating the experiences gained during the resultant, demand-based maintenance actions. The elaboration of complex, concerted smart data processing and smart learning methodology is subject of future research.

As an overview of smart fan features, **Table 1** provides some headwords of a SWOT analysis on the smart fan concept.

Table 1. SWOT analysis of the smart fan concept

Strengths	**Weaknesses**
Condition monitoring	More costly investment
Malfunction prediction	Need for complex knowledge
Energy management	
Cost-effective operation	Need for sensors also out of the fan
Integrated sensors	
Opportunities	**Threats**
Smart flow control	Malfunctions due to system complexity
Smart noise control	
Smart maintenance	Errors in electronics
Smart system learning	Cybercrime

7. CONCLUSIONS AND FUTURE REMARKS

The concept of smart industrial air technology / ventilation has been introduced in this paper, fitting to the Industry 4.0 perspective. The industrial implementation of smart fan concept has been illustrated in an evolutionary approach, in the sequence of common fans $\rightarrow$ advanced fans $\rightarrow$ smart fans, via two exemplary conceptual case studies. The "Gas engine power plant" and "Air technical separator" case studies are representative for axial and radial fans, respectively. The paper is summarized as follows.

1) Fan candidates for further development into smart fan status have been introduced in the two case studies, with features of *a priori* high efficiency; robust in-built toolkit with a potential of multipurpose fluid mechanics measurements; and *a priori* high resistance against solid contaminants.

2) Interacting concepts and the related data packages for smart fan features have been introduced as follows: efficiency monitoring and control; fluid mechanics-based condition monitoring; noise

monitoring and control; vibration monitoring; bearing temperature monitoring.

3) As support to noise monitoring and control, the concept of acoustically transparent duct, as well as optional application of textile air duct systems, have been recommended.

4) The extensive instrumentation being necessary for the aforementioned smart fan features have been detailed, and illustrated via operational schemes. The perspective of using DIY sensors in smart fan systems has been outlined.

5) In order to provide references for comparing with the actually measured and derived quantities, a *multilevel basis* has been proposed for referencing for the various tools of fan condition monitoring, upon availability: a) Legislative, standardized, and guideline references. b) Certified factory measurements on fans and drives. c) *Reference self-measurements.*

6) Concepts for complex and comprehensive smart processing and utilization of the gathered data, from a data science perspective, have been outlined.

7) A SWOT analysis has been delivered, in headwords, on the smart fan concept.

8) The following topics are subjects to further research and to gathering practical experience:

- Trend analysis and monitoring the degradation in fans;
- Instrumentation, data acquisition and processing, and trend analysis in acoustics-based condition monitoring of fans, optionally involving acoustically transparent ducts;
- Trend analysis in vibration monitoring for fans;
- Bearing temperature monitoring for fans;
- A complex, comprehensive treatment of all of the above features in smart data processing and smart learning methodology, from a data science perspective; and elaboration of well-designed actions on the air technical system as practical exploitation of the smart fan concept, e.g. demand-based maintenance.

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