SOFTSENSOR FOR THE CHARACTERISATION OF THE PROCESS FLUID

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SUMMARY

This paper introduces an intelligent fan equipped with a softsensor for the volume flow rate and composition of a two-component process fluid, as e.g. often found in chemical processes. This is done by combining the fans characteristic data with those of cheap pressure and temperature sensors as well as the mixture laws of a two-component gas. An example estimating the percentage of butane for a combustion flow is given. As the experiments show, the estimation uncertainty of the softsensor is 2 % for the butane concentration and 3 % for the volume flow rate and thus of the magnitude of the uncertainties of the used input data.

TOPIC

The main function of fans is supplying the required volumetric flow of process gas, among others for or from combustion processes, for chemical processes or for energy transport. The composition of the process gas is however impairing for process control as the uncertainty in gas composition is often accompanied by an uncertainty in the process mass flow. Thus, the operating point of the individual plant components (fan, control valve, heat exchanger, ...) can only be determined with a certain degree of uncertainty and the system may not be operated in its energetic optimum. Moreover, the knowledge of the operating point is essential for the safe operation of equipment, e.g. to avoid unwanted self-excited system vibrations. For diagnosis applications, e.g. leakage detection, the knowledge of the gas composition is as well essential.

Sensors measuring gas composition are costly. Thus, it is the aim of this paper to introduce an alternative method in the context of Industry 4.0: By using process knowledge, i.e. the fans characteristic data and the data of cheap existing sensors, to determine the properties of the process fluid by a model based data fusion. [1]

METHOD

Mass flow and thermodynamic properties are simultaneously determined in real time and inline by analyzing the performance of the fan along with the information provided by low cost sensors, i.e. temperature and pressure sensors up- and downstream of the fan. The operating behavior of the fan is known in form of characteristic maps from measurements on component test rigs, analytical calculation, numerical simulations or by using scaling methods [3,4].

To reduce the amount of values a dimensionless map of the form

$$\psi \coloneqq \frac{2\Delta p}{\varrho \pi^2 n^2 d^2} = \mathrm{f}\left(\varphi \coloneqq \frac{4Q}{\pi^2 n d^3}, Re \coloneqq \frac{\varrho \pi Q}{\mu}\right), \tag{1}$$

$$\eta \coloneqq \frac{\Delta p Q}{P_{el}} = \mathrm{f}\left(\varphi \coloneqq \frac{4Q}{\pi^2 n d^3}, Re \coloneqq \frac{\varrho \pi Q}{\mu}\right) \tag{2}$$

is used. The dimensionless pressure number ψ describes the pressure rise over the fan Δp and the efficiency η the electrical input power P_{el}. φ is the delivery number describing the transported volume flow rate Q while the Reynolds number Re describes the dimensionless rotational speed n of the fan. Further parameters are the diameter of the fan d, the density of the transported fluid ϱ and its dynamic viscosity μ.

In most applications the pressures p_1 and p_2 up- and downstream of the fan are measured, as is the rotational speed n and the electrical Power input P_{el}. Thus, in equations (1) and (2), the volume flow Q and the thermodynamic properties of the process gas (ϱ, μ) are unknown. To determine all three quantities by using a softsensor, one further information is necessary.

This information may be taken from the regulating valve as exemplary presented in [1]. In the context of this paper however, a two-component fluid consisting of air and butane is considered. Thus, the two gas properties can be collapsed into one property, i.e. the fraction of butane $c_{C_4H_{10}}$, approximating the mixture as an ideal gas. With the molar amount ratios

$$x_i = \frac{c_i / M_i}{\sum_i c_i / M_i} \tag{3}$$

for the fractions c_i of the two fluids air and butane with its molar masses $M_{air} = 28.97\ \mathrm{g/mol}$ and $M_{C_4H_{10}} = 58.12\ \mathrm{g/mol}$, the dynamic viscosity μ of the air-gas mixture writes

$$\mu = \frac{\sum_i \mu_i x_i \sqrt{M_i}}{\sum_i x_i \sqrt{M_i}}. \tag{4}$$

μ_i are the dynamic viscosities of air and butane $\mu_{air} = 18$ µPas and $\mu_{C_4H_{10}} = 7.3$ µPas respectively. Using the ideal gas equation, the density ϱ of the mixture writes

$$\varrho = \sum_i c_i \frac{p_1}{RT_1} M_i, \tag{5}$$

with R being the general gas constant and T_1 the gas temperature at the inlet section, which can be measured with a cheap sensor.

Thus, equations (1) - (5) form an implicit, non-linear algebraic equation system with the variables Q and $c_{C_4H_{10}}$which usually shows a clear solution. Since the measurement data set p_1, p_2, n, P_{el}, T_1 is associated with uncertainties, a probabilistic approach is used. Applying a Monte-Carlo Simulation with different input data within the uncertainty range not only the searched variables Q and $c_{C_4H_{10}}$ are found, but also the associated uncertainties ΔQ and $\Delta c_{C_4H_{10}}$.

EXPERIMENT

The test rig as depicted in figure 1 consists of a silencer, a temperature sensor, the radial fan, a pressure sensor, a throttle valve and a flow sensor for validation. The use of the silencer is solely to reduce the noise level during the experiment. The associated pressure drop in the silencer can be neglected. For the flow measurement a thermocouple volume flow sensor is used. The pressure sensor is a differential pressure sensor to the atmosphere.

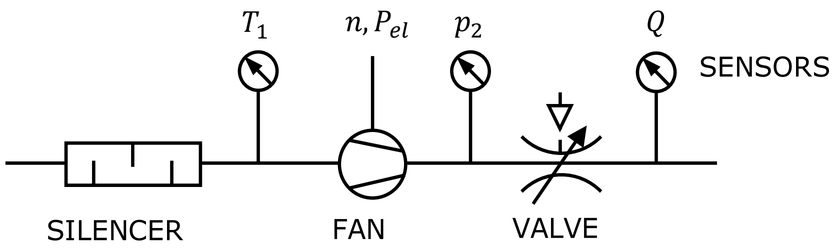

Figure 1: Test Rig Design

CHARACTERISTICS

As measuring with butane is costlier than with air, the characteristic map of the fan is measured using air as a process fluid. The rotational speed is chosen, such that the Reynolds numbers

$$Re = \frac{\varrho(c_{C_4H_{10}})\pi n_N d^2}{\mu(c_{C_4H_{10}})} \tag{6}$$

are equal to those, that would be gained if the he fan was operated at nominal rotational speed n_N with butane fractions $c_{C_4H_{10}}$ of $0, 15, 30, 45$ and 50 percent respectively. For each rotational speed 8 to 10 different valve positions are analysed. The obtained characteristic maps are depicted in figure 2. Numeric values are removed due to confidentiality reasons.

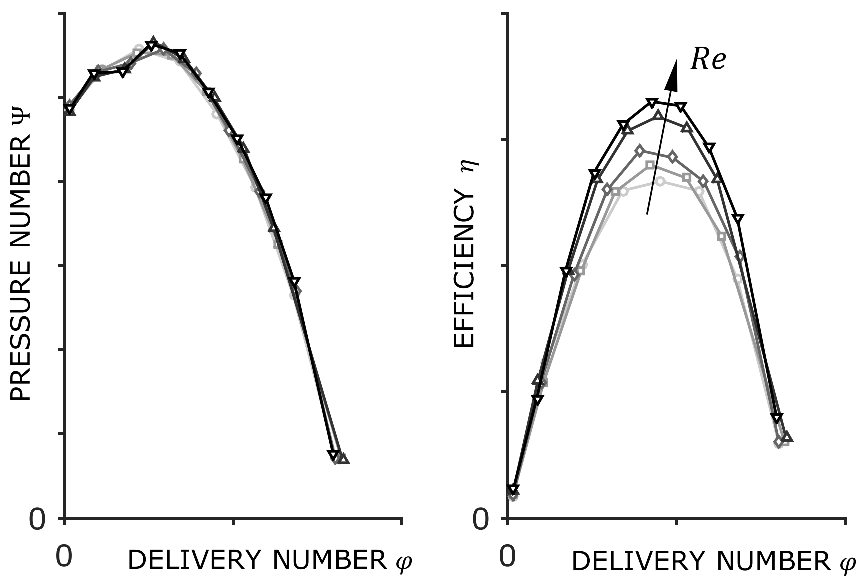

Figure 2: characteristic map of the considered fan

The pressure number is basically independent of the Reynolds number. The deviations in the low delivery range are due to stall in the impeller. Considering the efficiency however, a significant dependency on the Reynolds number is prominent as the efficiency increases with increasing Reynolds number, i.e. butane concentration.

This prominent dependency enables the determination of the fraction of butane in the process gas as the Reynolds number is a function of the viscosity and the density of the mixture and thus, of the butane concentration. The resulting functions $\mu = f(c_{C_4H_{10}})$ and $\varrho = f\left(c_{C_4H_{10}}\right)$ are depicted in figure 3 for nominal temperature $T_1 = 293.15$ K.

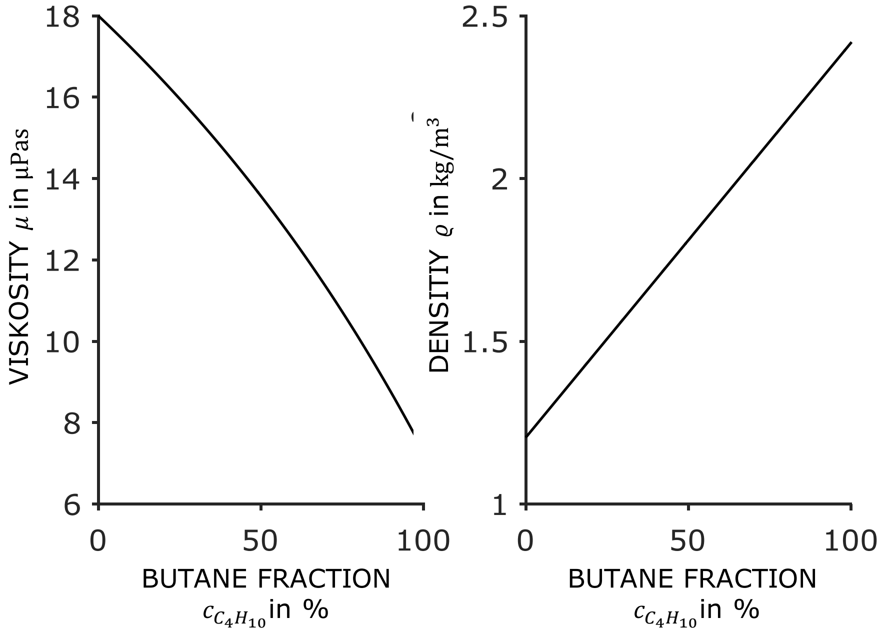

Figure 3: characteristic map of the considered fan

VALIDATION

The validation of the softsensor is performed on the same test rig as the measurement of the characteristics of the fan. In contrast to the measurement of the characteristics, the valve position is fixed, and the rotational speed is varied. The range is set to correspond to the measured Reynolds number range. Up to now only experiments with air are performed. The measurement uncertainties amount up to about 5% for each of the five quantities T_1, n, P_{el}, p_2, Q.

Figure 4 shows the analysed measurement points in the $\Delta p, Q$-area. The uncertainties are depicted by error bars (if the uncertainties are small they are hidden behind the markers). For better orientation the characteristic of the fan and the system characteristics (approximated by $\Delta p = \zeta_i Q^2$) are plotted. Numeric values are again removed for confidentiality reasons.

The measurement data from the temperature and pressure sensors T_1 and p_2 and the information n and P_{el} from the fan converter are used as input for the softsensor as well as the characteristic functions $\psi = f(\varphi, Re)$, $\eta = f(\varphi, Re)$, $\mu = f(c_{C_4H_{10}})$ and $\varrho = f\left(c_{C_4H_{10}}\right)$. The data from the volume flow sensor and the known butane concentration $c_{C_4H_{10}} = 0$ are used as a reference to evaluate the quality of the softsensor reliability.

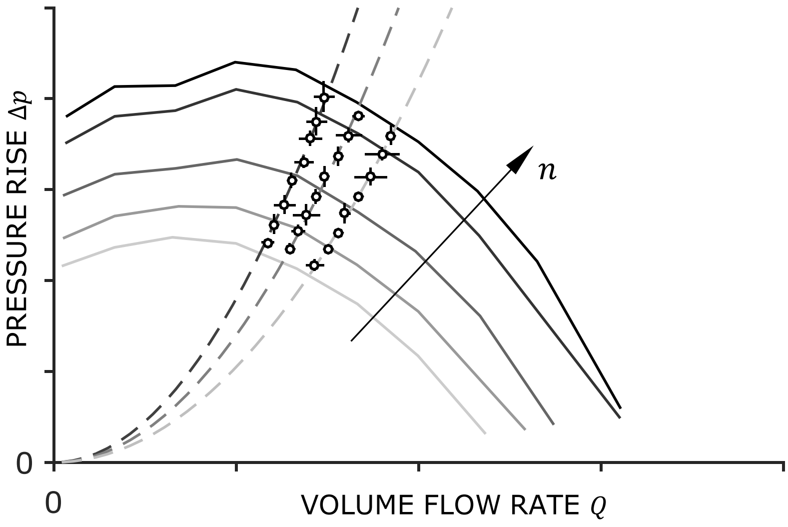

Figure 4: characteristic map of the considered fan

In figure 5, the measured/ known validation data is depicted together with the calculations obtained by the softsensor, each with its associated uncertainties. The volume flow rates are referred to the maximum measured value. The uncertainties of the softsensor are obtained by a Monte Carlo simulation, which solves the system of equation for different input data sets in the uncertainty range. This method is used, as a straight-forward error propagation is not possible for a nonlinear solver.

The quality of the softsensor for the volume flow rate Q determined by the relative error $J_Q = |Q_{meas} - Q_{estim}|/Q_{meas}$ and for the butane concentration by the absolute error $J_c = c_{C_4H_{10},estim}$ (as a relative error analysis is not possible due to $c_{C_4H_{10}} = 0$), as depicted below.

Thus, the average uncertainty using the softsensor amounts to 6 % which is about the same magnitude as the measurement uncertainty. The average relative error $\overline{J_Q}$ is 4 % which is as well in the magnitude of the uncertainty. The same holds for calculation of concentration with an average uncertainty of 1.5 % and an average absolute error $\overline{J_c}$ of 1.5 %.

Consequently, the softsensor yields reliable results for the determination of the volume flow rate and the characterisation of the process fluid. Hence, it is possible to save costly volume flow rate and gas composition measurement by applying a softsensor concept using known fan characteristic and converter data together with cheap pressure and temperature sensors instead.

SUMMARY AND OUTLOOK

In this paper a softsensor for volume flow and process fluid characterization is introduced. The idea is to use available information and cheap (mostly already existing) sensors to substitute expensive volume flow and gas composition sensors. It is shown that for a two-phase fluid, the characteristic map $\psi = f(\varphi, Re)$, $\eta = f(\varphi, Re)$ and the mixture laws $\mu = f(c_1, c_2)$ and $\varrho = f(c_1, c_2)$ contain enough information to calculate the volume flow and gas composition within the uncertainty ranges. (If gases with more or unknown components are to be characterized, additional information is necessary, e.g. from other sensors or components such as the valve)

The validation is done for one set of data measured with air. Therefore, the aim is to add more validation points using more valve settings and gas compositions in future work. Furthermore, it is desirable to measure another fan to have more substantiated validation.

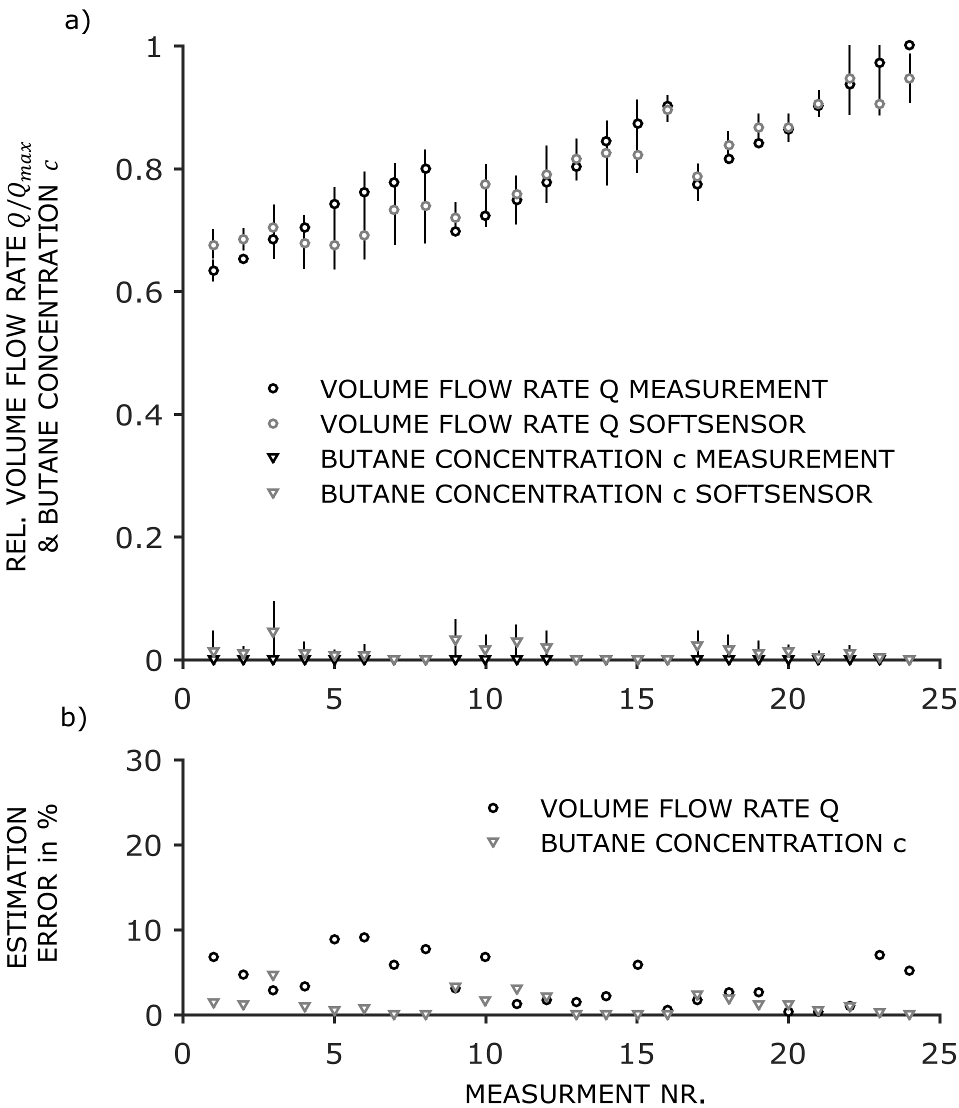

Figure 5: measured data and calculated values (a) and the resulting estimation errors (b)

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