Flowmetering Faults and their Causes Exemplified with the Active Pressure Methods

*By A. BRUEMMER**

With the liberalization of the gas market the demand for reliable and highly precise flowmeter installations rises. Certainly, the measuring accuracies of various measuring installations ascertained on the test bench are already quite remarkable, however, practice shows that the accuracies achieved under field conditions often are considerably lower. The reasons therefore can be categorized into three types considering measuring installations that work according to the active pressure principle (such as orifice plates, nozzles, Venturi tubes). The first category comprises all the causes that lead to a falsification[1] of the pressure within the fluid at the pressure tappings. This includes, e. g. fluidically caused deviations of the pressure as a result of swirl, unsteady flows, pressure pulsations, respectively. All the influential factors that falsify the active pressure between pressure tappings and differential pressure transducer belong to the second category (including the volumes within the differential pressure transducer). This group includes errors due to the compensating flows or acoustic resonances within the gauge lines. The third category finally comprises flowrate measurement erros caused by the differential pressure transducer and the following equipment.

After a brief explanation of the flowrate measuring via active pressure method the following article elucidates the dominant sources of error per category and documents their shapes of appearance with examples from practice. Further more different ways to avoid or to correct these errors are pointed out.

1 FLOWRATE MEASURING VIA ACTIVE PRESSURE METHOD

Within this method a contraction (such as an orifice plate, nozzle, Venturi tube) is fixed inside the pipe. Because of the contraction the flow velocity increases, whereas the pressure decreases. A typical flow structure and pressure distribution occurs along the axis of the pipe. Concerning an orifice plate a qualitative flow pattern and pressure distribution is shown in Fig. 1. Calipering this pressure distribution at two positions a differential pressure can be measured. The arrangement of the tap ports is defined for every flowmeter in [1]. Using the differential pressure the flowrate can be calculated. In order to get the delivered mass the flowrate has to be integrated once with respect to time.

2 REALIZING, EVALUATING AND REDUCING THE SOURCES OF ERROR

2.1. Influence of flow conditions

The conditions to get the expected accuracies via active pressure methods are mentioned in [1]. Among other things this includes a non-swirling and steady flow. In case a swirl is present, it may be avoided by using special flow conditioners, which are quite easy installed. In principle the effects of swirl and flow conditioners on the measuring accuracy of orifice plates are investigated in [2]. In contrast to this it is much more difficult to produce a steady flow without pressure or volume pulsations. The reasons for this are multifarious. On the one hand the operational staff often does not know that there are unsteady flow conditions (e. g. caused by acoustic resonances) inside the pipe. On the other hand pulsation damping devices are in general cost-intensive and the implementation sometimes requires great effort. In additions there remains the question concerning the permissible residual pressure and volume pulsations.

Whether perturbing pulsations within the pipe occur can be verified by measuring the differential pressure immediately at the differential pressure device – thus, without possibly existing long gauge lines. For this purpose a differential pressure transmitter with a high limiting frequency should be used. The time signal or the transformed signal in the frequency range should be stored. It is recommendable to repeat the measurements at various operating conditions (e. g. flowrates, temperatures).

An example for such a differential pressure signal in conjunction with the amplitude spectrum is shown in Fig. 2. In contrast to the required constant signal the differential pressure is subject to considerable fluctuations. These oscillations around the time-mean value $\Delta p_0 = 67$ mbar lead to even negative differential pressures. In conjunction to this one might suppose a reverse

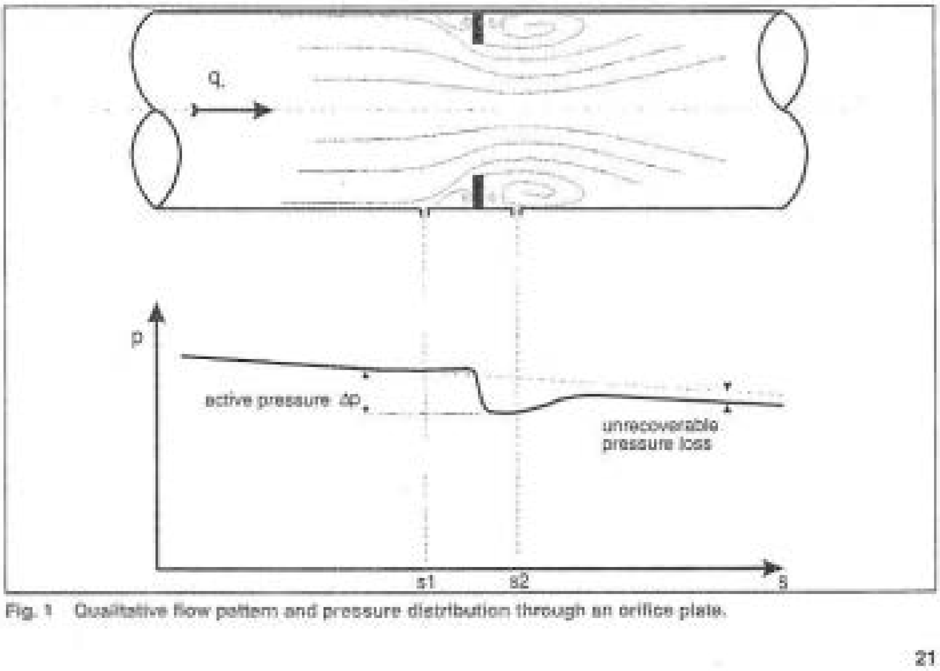

Fig. 1 Qualitative flow pattern and pressure distribution through an orifice plate.

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*Dr.-Ing. Andreas Brümmer, Köster Beratende Ingenieure GmbH, Rheine, Germany.

[1] Falsification refers to the deviation of the time-mean active pressure from the value that, with the same mass flow, would occur at the measuring installation under ideal (error free) conditions.

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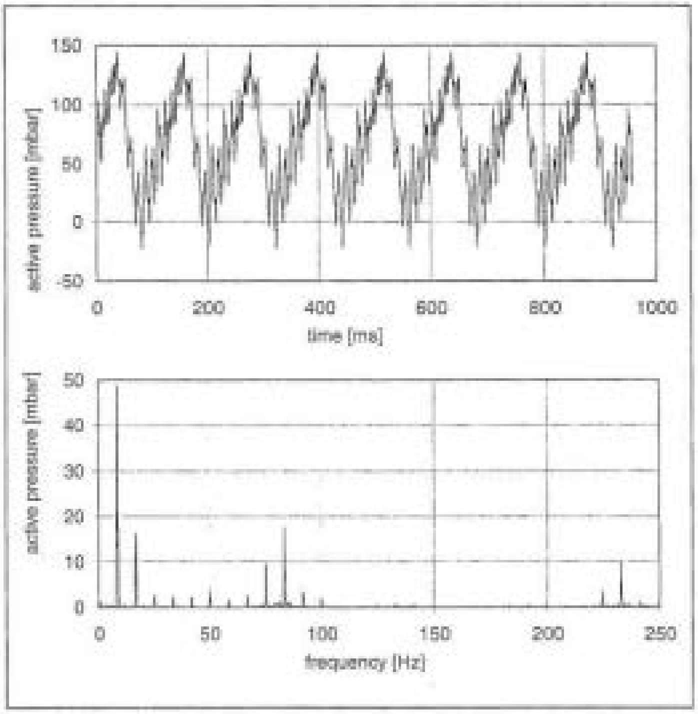

Fig. 2 Time signal and amplitude spectrum of a differential pressure measured at a standard orifice plate (time-mean value Δp_0 = 67 mbar).

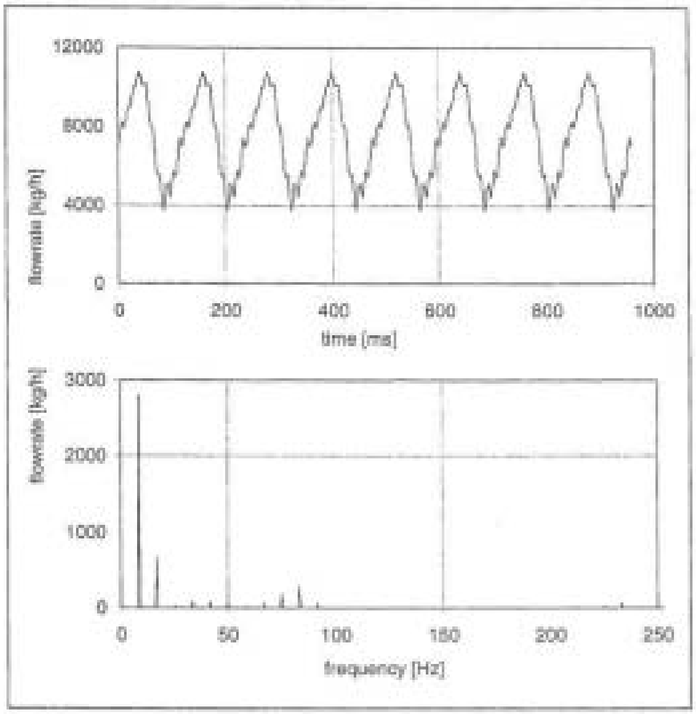

Fig. 3 Time signal and amplitude spectrum of the flowrate passing through the standard orifice plate (time-mean value $q_{m,IST}$ = 7500 kg/h).

flow. However, it will be shown later that in this case a backflow does not occur.

Based on the amplitude spectrum the reason for the unsteady flow is obvious. It is generated from a reciprocating compressor which is situated upstream of the orifice plate. The discharge frequency of the compressor matches the determined frequency of the differential pressure pulsations (Fig. 2).

In case the time-mean differential pressure is used to calculate the mass flowrate the result is a value of $q_{m,Fehl}$ = 7776 kg/h. However, this mass flowrate does not correspond to the true mass flow $q_{m,IST}$ that passes through the orifice plate. In order to get the actual value $q_{m,IST}$ it is necessary to solve the unsteady Bernoulli equation [3]. This equation can be transformed into a non-linear differential equation using the assumption mentioned in [4, 5]. In conjunction with the measured differential pressure, the internal diameter of pipe and orifice plate the differential equation can be numerically integrated (e. g. using a Runge-Kutta method [6, 7]). As a result the instantaneous values of the mass flowrate are obtained.

Carrying out these calculations using the measured differential pressure according to Fig. 2, it follows the corresponding mass flowrate (Fig. 3). Even though the differential pressure is temporary negative the mass flowrate remains positive. Hence, a reverse flow does not occur. The main reason for the temporarily negative differential pressure is a high frequency interfering disturbance. Out of inertia forces and the connected local accelerations already weak high frequency flow pulsations cause considerable differential pressure fluctuations. Adding the time-main flow to the minor flow fluctuations a reverse flow does not result. By integrating a period of flowrate oscillations the time-mean value $q_{m,IST}$ = 7500 kg/h is obtained. In comparison the calculated mass flowrate of $q_{m,Fehl}$ = 7776 kg/h, determined from the time-mean differential pressure, is almost 4% too high. This deviation cannot be rectified by averaging the square root of the differential pressure signal, like it is often recommended. On the one hand it is difficult to extract a reasonable square root from a measured negative differential pressure. On the other hand this kind of averaging is not the right way concerning the differential pressure signals caused by local accelerations, because there is mainly a linear correlation between these quantities.

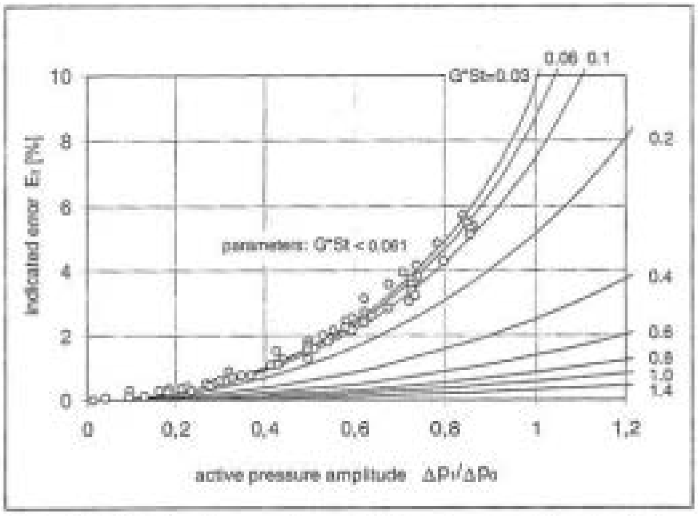

Fig. 4 Calculated and measured errors ET as a function of the sinusoidal differential pressure amplitude $\Delta p_1/\Delta p_0$ for various parameters G · St.

The principle influence of a sinusoidal differential pressure oscillation for different parameters (e. g. geometric parameter G, Strouhal number St [7]) on the measuring E_T,

$$E_T\,[\%] = \left(\frac{q_{m,FEHL}}{q_{m,IST}} - 1\right) \cdot 100$$

is shown in Fig. 4. As expected the error E_T enlarges with increasing amplitude $\Delta p_1/\Delta p_0$ and decreasing product G · St. For comparison and verification measured values [8] are outlined too.

2.2. Influence of the connecting tubes

The absolute pressure signals at the bores of the pressure tappings are passed through the gauge lines to the differential pressure transducer. Without disturbances there will be no flow inside the gauge lines. In contrast pulsations at the pressure tappings or flow turbulences can cause unsteady flows in the connecting tubes and thus serious errors in the indicated time-mean differential pressure, especially if there are acoustical resonances in the connecting leads.

As an example Fig. 5 shows the amplitude

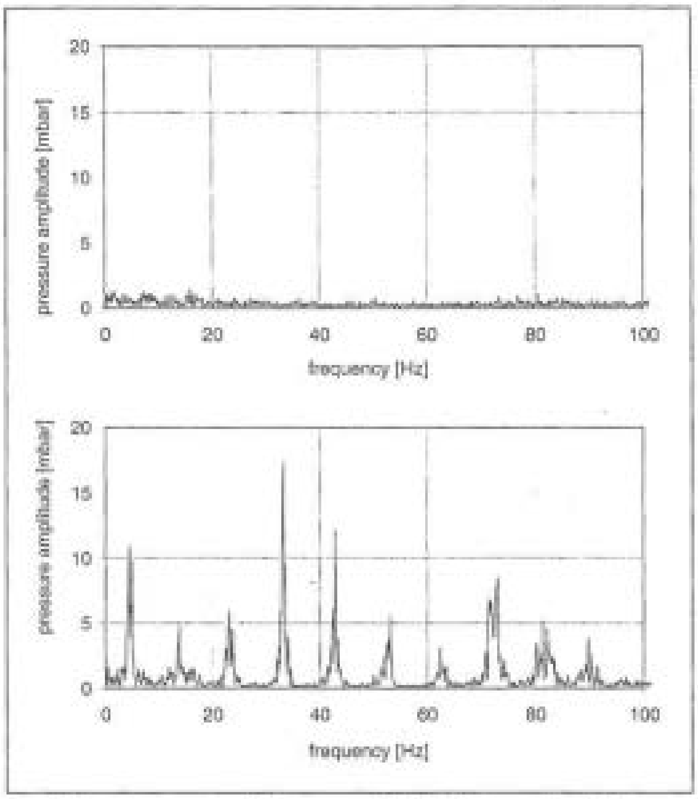

Fig. 5: Amplitude spectra of the measured differential pressure with (upper figure) and without (lower figure) long connecting tubes.

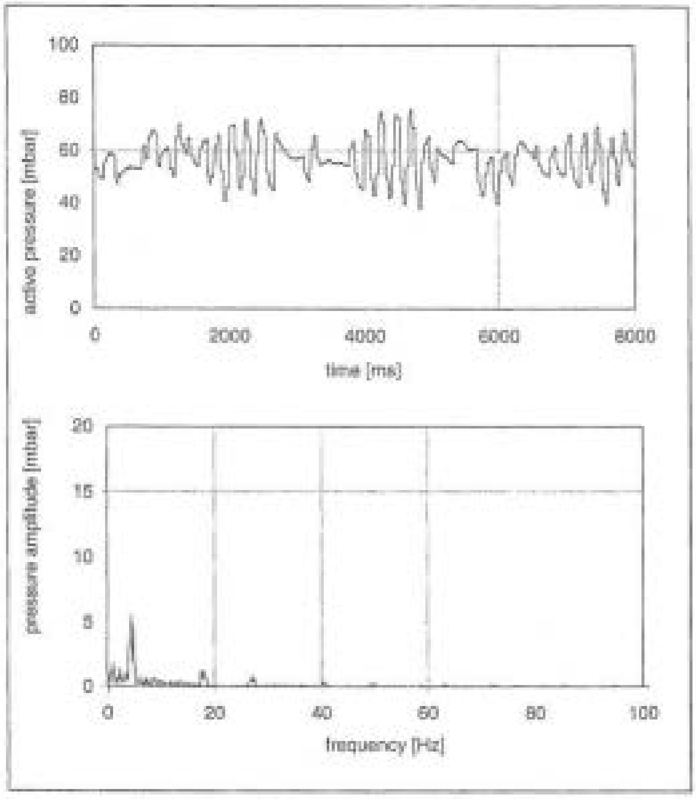

Fig. 6: Time signal and amplitude spectrum of slow-response manometer signal (present differential pressure signal see Fig. 5 below).

spectra of the differential pressure signals, measured directly at the flowmeter (upper figure) and at the remote differential pressure transducer (lower figure). In this case the flowmeter is an averaging pitot tube fixed in the pipe downstream of a radial flow compressor delivering natural gas.

No significant differential pressure fluctuations are observed inside the gauge lines close to the flowmeter. In contrast there are considerable pressure pulsations at the end of the connecting tubes. The frequencies of these pulsations correspond to the natural frequencies of the connecting tubes. By using the speed of sound of 400 m/s and the given length of the connecting tubes of 21.3 m the first natural frequency of 4.7 Hz (λ/4-resonator) can be evaluated. Further natural frequencies within the gauge lines are 14 Hz (3/4 λ), 23.5 Hz (1 1/4 λ), 32.9 Hz (1 3/4 λ), 42.3 Hz (2 1/4 λ) etc.. Considering Fig. 5 it is obvious, that there are increased differential pressure amplitudes especially at these frequencies.

These acoustic resonances can cause indicated errors in various ways. For example the recommended procedure applied to the measured pressure pulsations shown in Fig. 5 (lower figure) will cause significant errors, because primary the square root of the differential pressure would be calculated.

However, in order to compensate the acoustic resonances in the connecting leads a rather time-mean value of the differential pressure signal is more appropiate. On the other hand the resonances could lead to a variation of the time-mean pressure along the gauge lines. This error results, in part, from the fact that the head loss factors (flow resistances) into and out of a contraction are not equal or nonlinear damping devices are installed in the connecting tubes. A typical measured distribution of the time-mean pressure profile along a gauge line with strong pulsations present is shown in [9]. In this case the active pressure measured by the differential pressure transducer is not proportional to the flowrate, which runs through the flowmeter. In consequence considerable errors may occur.

Unfortunately, global rules to avoid the outlined sources of error are not available at present. However, it is possible to recommend a number of design rules [4]:

- The tube connecting the pressure tapping to the manometer must be as short as possible. Lengths of head should be clearly shorter than the pulsation quarter-wave length.
- Abrupt changes of the cross section must be avoided as well as volumes of gas within the connecting tubes.
- The connecting tubes must be designed geometrically equal (e. g. same lengths).
- The natural frequency of the sensing element must be much lower than the pulsation frequency, especially the first acoustic resonance frequency of the connecting tubes.

2.3. Influence of the differential pressure transducer

In case the natural frequency of the manometer does not fall below the acoustic resonance frequency of the connecting tubes, the output signal for example looks like in Fig. 6.

In comparison to the actually present differential pressure signal (Fig. 5 below) the filter effect of the transmitter becomes apparent. While the low-frequency pressure pulsation of 4,7 Hz is passed through, all high-frequency pressure pulsations are filtered out. In relation to the measuring range of the averaging pitot tube (0 mbar to 90 mbar) the output signal oscillations are much too high. Further more there is no correlation between these signals and the flowrate in the pipe, as already described. However, the following flow-computer does not make this distinction. The result is a measuring error that in this case has lead to serious control-technique problems of the radial flow compressor.

3 ADVISED ACTION

Taking into account the outlined correlations it is recommended to examine the cost-intensive or technical process-relevant flowmeter installations with respect to existing perturbations.

Thus, in the first step the differential pressure should be measured immediately at the flowmeter – hence, without possibly existing long connecting tubes – using a fast response differential pressure transducer. As long as the resulting effective differential pressure pulsations are smaller than 10 % of the time-mean value of the differential pressure measuring erros due to pulsating flows are not to be expected [10] (Fig. 4). Otherwise the expected measuring error should be calculated according to the method outlined above and described in detail in [7]. If it is possible to associate the measured pressure pulsations unambiguously and reproducibly to the operating conditions, the once determined errors E_T can be used in the following to correct the indicated flowrate (correction according to table).

In contrast, if this association is not possible, the differential pressure could continuously be measured by means of a fast response transducer and the true flowrate could be calculated on-line (»on-line« correction).

On principle it is preferable to identify the cause of the determined pulsations. Knowing the working mechanism sometimes surprisingly economical measures can be realized (e. g. by means of pulsation damping-plate according to the KÖTTER principle [11]) and thus the measuring accuracy can be increasd considerably.

In the second step the influences of existing gauge lines and the differential pressure transducer are to be examined. It is recommended to compare the measured time-mean differential pressure at the flowmeter to the value indicated by the installed differential pressure device. In case of significant deviations it points to the fact that acoustic resonances within the gauge lines are present. Therefore, the connecting tubes are to be shortened considering the rules mentioned in chapter 2.2. Particularly in conjunction with »on-line« corrections the maximum permissible lengths of the gage lines have to be adjusted precisely to the individual requirements of the regarded flowmeter.

4 CONCLUSIONS

After a brief explanation of the flowmetering by means of active pressure devices the dominant sources of error concerning the indicated flowrate are outlined and categorized into three types. Recommendations to realize, evaluate and reduce these sources of error are given.

The first category comprises sources of error that lead to a falsification of the pressure within the fluid of the pressure tappings. This includes for example pulsation flow conditions, that cause an unsteady active pressure and hence are responsible for serious errors in the indicated flowrate. A procedure to correct these errors is outlined. The method is based on the measured active pressure using a fast response differential pressure transducer. The procedure is verified using experimental results and applied to an example from real life.

The sources of error, falsifying the differential pressure between the pressure tappings and the manometer, are part of the second category. This group comprises for example acoustic resonances within the connecting tubes. The characteristic consequences of these resonances are explained using measuring results. In addition principle rules in order to avoid thes problems are mentioned.

The third category includes all sources of error between the differential pressure transducer and the indicated flowrate. As an example the influence of a slow response differential transducer is described in case acoustic resonances within the gauge lines are present.

Finally, practical criteria are given in order to identify, evaluate and reduce sources of error at cost-intensive or technically process-relevant flowmeter installations.

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