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Electrocapillary elements. III. Properties and applications to variable pressure manometers

Z. KOCZOROWSKI, E. KUCHARSKA-GIZIEWICZ, Z. FIGASZEWSKI

Institute of Basic Problems of Chemistry, Warsaw University, Warsaw, Poland

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The characteristics of electrocapillary elements with their filling subjected to vibrations by mechanical and electrical harmonic input signals of frequencies in the range 0.003–30 Hz as well by voltage or pressure jump were studied. The idea of variable pressure or pressure jump measurement by means of an electrocapillary transducer and a model of such a manometer are presented.

1. Introduction

Electrocapillary elements have been hitherto studied mostly at frequencies higher than 20 Hz and data on measurements carried out at lower frequencies contained in the literature [1–3] are fragmentary. It is known that electrocapillary transducers cannot operate at zero frequency because of their voltage-generating character [4]. Thus it was necessary to study more systematically the characteristics of electrocapillary elements in the very low frequency range. It will enable the possible frequency ranges of vibration sensing to be extended [4–6] and will lead to new applications of electrocapillary elements in pressure measurement described in this paper and part IV. It is also essential to determine the range of input signal amplitudes for which the output signal, particularly the short-circuit current, is proportional to the input; in this range the experimental results can be analysed in terms of determined models [5–8].

It has been the purpose of this work to present some properties of electrocapillary transducers, oscillators and resonators [7, 8] in the frequency range of about 0.003 Hz up to 10 Hz. The idea and an example of the construction of an electrocapillary variable pressure manometer are also presented. The possibility of applying electrocapillary transducers to the measurement of slowly varying pressures in medicine was reported earlier by Elliot *et al.* [2] and by Yoshimoto [3].

2. Experimental

The preparation of materials and of electrocapillary elements have been described earlier [4, 7, 8]. The elements contained a 0.5 N Na_2SO_4 + 0.5 N H_2SO_4 solution and their resonance frequencies ranged from 10 to 30 Hz. Their most important construction parameters are as follows: the number of interfaces n, the capillary diameter ϕ, the mass of the filling m, and the lengths of the gas columns at the capillary ends, ${}_1L_p$ and ${}_2L_p$ (see Table 1).

The study comprised measuring the open-circuit voltage, U_{open}, the short-circuit current, I_{sh}, and the filling displacement amplitude, δ. These experimental data were used to calculate the internal impedance of the element and the electrocapillary coefficient α [7–9]. The internal impedance was also determined by the current–voltage method [7, 8] where the element was polarized by an alternating voltage. In this work the low-frequency limit of vibrometric measurements was decreased from 20 to 5 Hz. In the studies at low frequencies the electrocapillary resonator has been used as the element and the filter method [7, 8] shown diagramatically in Fig. 1 served as the measurement method. The short-circuit current in the vibrometric and filter measurements has been determined as the voltage drop across a low load resistance of the order of magnitude of 1–10 kΩ. The load resistance has been adjusted in such a way that the output current is resistance independent; the proportionality of

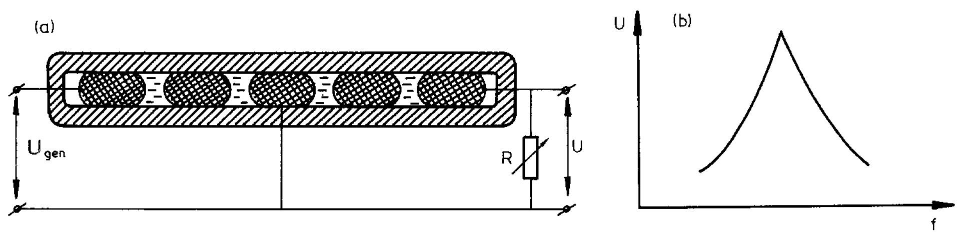

Fig. 1. The measurement of the filter characteristic of an electrocapillary resonator (a) and its shape (b) U_{gen} is the input voltage, R the load resistance, and U the output voltage.

output voltage to the load resistance has been checked. The filter method decreased the low-frequency limit of the output signal of transducers to about 0.003 Hz. In the frequency range from this value up to 20 Hz the amplitude of filling displacement was determined by means of a stereoscopic microscope. Alternating pressure was generated by means of an electrodynamical generator connected with an elastic metal bellows. This system conveyed the pressure variations to an open electrocapillary element by means of a PVC tube. The voltage and pressure jumps were applied from a constant voltage feeder and from a manostat, respectively.

3. Results and discussion

Typical dependences of the outputs, i.e. short-circuit current and filling displacement, on the amplitude of the stimulating input signals are presented in Fig. 2 [10]. The figure also illustrates the linear range of the amplitude characteristics of the electrocapillary elements. It has been found that the open resonators had a linear response up to about 25 mV per interface of the oscillator; at higher voltage values a transformation of the filling structure occurs. Sealed resonators with air columns about 5 cm long, disposed symmetrically at the capillary ends had a linear response up to about 60 mV per mercury–electrolyte solution interface; at higher voltage values the characteristic is curved and saturation is attained at about 120 mV per interface.

It has also been found that the output signal varies linearly with harmonic pressure variation within the pressure amplitude limit which could be generated by the apparatus used. The linear range and hence the element sensitivity depend primarily on its internal stiffness which can be controlled by adjusting the gas volume within the element, i.e. the ${}_1L_p$ and ${}_2L_p$ values (see Table 1).

Typical frequency characteristics of short-circuit current, I_{sh}, and filling displacement δ are presented in Figs. 3 and 4. The dependences shown there demonstrate that the displacement is constant and the short-circuit current is proportional to frequency below the resonance value. The plateau range observed in Fig. 4 determines the frequency range in which the piston mechanism of the filling movement predominates [9]. A proportionality between the short-circuit current and the frequency appears even at infinitely low frequency [7, 8].

The frequency characteristics of the short-circuit current and of the open-circuit voltage as measured at the output terminals of an open electrocapillary resonator are shown in Fig. 5. Values

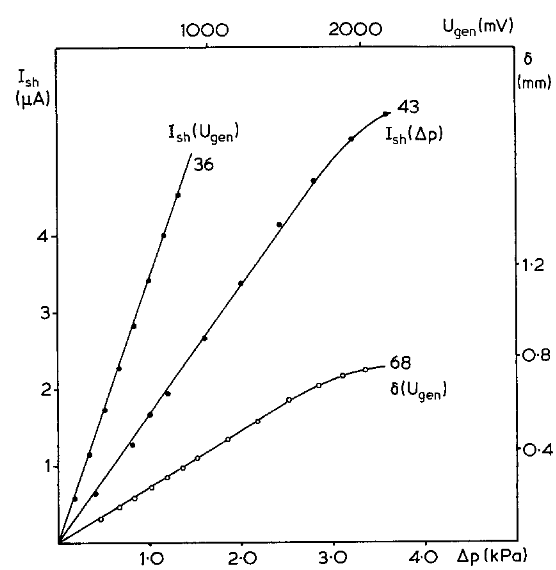

Fig. 2. Dependence of the short-circuit current and the displacement on the pressure and the applied voltage.

Table 1. Construction parameters of electrocapillary elements

Number of element	n	ϕ (mm)	m (g)	${}_1L_p$ (cm)	${}_2L_p$ (cm)
20	14 + 14	0.40	0.086	4.0	4.0
21	14 + 14	0.47	0.125	5.0	5.0
22	14 + 14	0.68	0.187	5.0	5.0
23	14 + 14	0.78	0.287	5.0	5.0
24	14 + 14	0.35	0.071	5.0	5.0
36	14 + 14	0.47	0.125	5.0	5.0
43	14 + 14	0.63	0.211	5.0	∞
44	14 + 14	0.63	0.211	5.0	5.0
56	14 + 14	0.60	0.182	5.0	5.0
68	16 + 16	0.37	0.087	1.58	2.46
71	8 + 8	0.37	0.057	∞	0.69

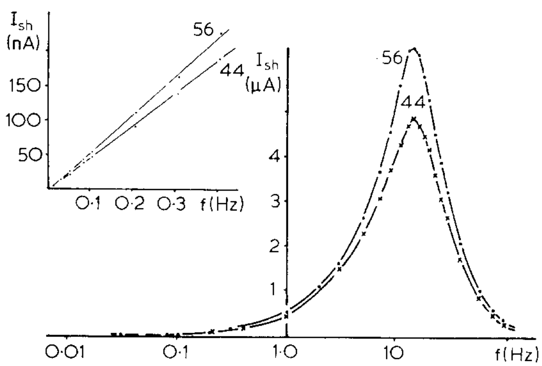

Fig. 3. The frequency characteristic of the short-circuit current.

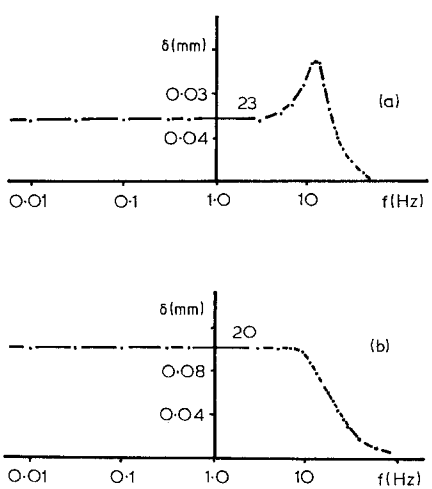

Fig. 4. Frequency characteristics of filling displacement for the elements: (a) with a small damping, (b) with a large damping.

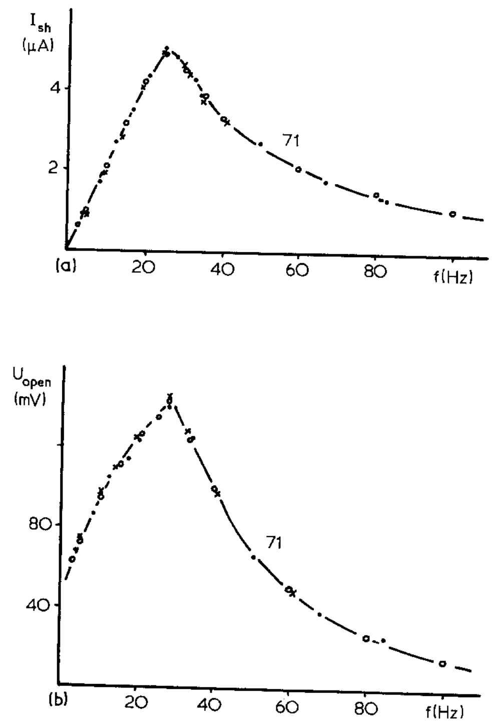

Fig. 5. Comparison of frequency characteristics of short-circuit current and open-circuit voltages: in vibrometric conditions $\ddot{x}_0 = 1.23\,\mathrm{m\,s^{-2}}$; in filter conditions $E_{gen} = 236$ mV; in harmonic pressure variation conditions, $\Delta p = 1.0$ kPa.

have been recorded for the element stimulated to vibrate by a harmonic pressure variation or by harmonic voltage variation. The amplitudes of the stimulating signals have been chosen in such a way as to obtain the same short-circuit current value at the resonance frequency.

The dependences shown demonstrate the

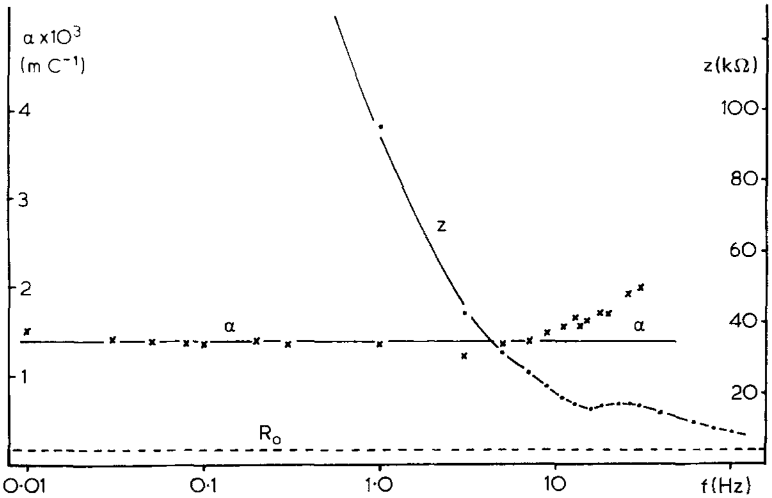

Fig. 6. Frequency characteristics of electrocapillary coefficient α and of inner impedance for the element 44 (see Table 1).

equivalence of mechanical and electrical stimuli in the movement of the element filling [7, 8, 10] and suggest that the same transduction mechanism is operating.

A typical frequency characteristic of the electrocapillary coefficient α is presented in Fig. 6 together with the frequency characteristic of the internal impedance. A constant value over a wide frequency range is typical and is in agreement with the discussion presented in [9]. Deviations from a line parallel to the abscissa which appear from the high-frequency points are due to errors resulting from a considerable contribution of electrolyte solution resistance to the internal impedance.

Fig. 7 shows the dependence of the reciprocal of the electrocapillary coefficient on the internal diameter of the capillary used for the element construction. The elements differ only in diameter.

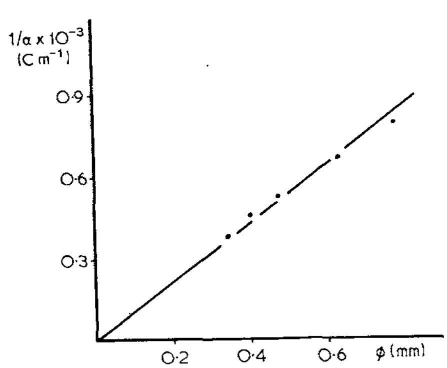

Fig. 7. Dependence of α^{-1} on capillary diameter for the elements 20–24 (see Table 1).

The dependence of $1/\alpha$ on the capillary diameter confirms that the piston mechanism plays a decisive role in the energy transformation for this type of electrocapillary element construction.

Attempts have been made to determine the sign of the charge generated at the output terminals of an element stimulated to move by a pressure or voltage jump. It has been found experimentally that the filling of an electrocapillary element thus stimulated generates a higher potential at the output terminal to which the filling moves, as illustrated in Fig. 8. This is in agreement with the observations of mercury droplets sinking in an electrolyte solution [11] and contradicts the results of [1].

4. The concept and the construction of a variable pressure manometer

According to the general equivalent circuit [7, 8] an electrically open electrocapillary transducer can be used for measuring variable pressures at frequencies below the resonance frequency ($f \ll f_0$) provided the impedance of the mercury–electrolyte solution impedance consists mainly of a capacitive component. In this case the general equivalent circuit assumes a simplified form presented in [5].

The equivalent circuit of a variable pressure manometer is identical to the equivalent circuit of an acceleration meter [5] but the variable mechanical force which stimulates the filling vibrations operates in a different way in the two cases: for

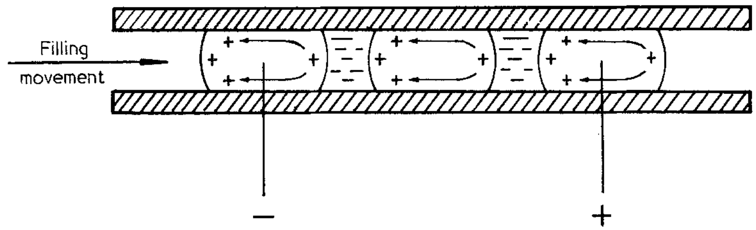

Fig. 8. Diagram explaining the presence of electrical effect at the output of the electrocapillary element resulting from its movement.

the acceleration meter it is the casing vibrations which are transferred to the filling whereas in the manometer the force is caused by a variable pressure of gas in direct contact with the filling (Fig. 9).

The mechanical force F acting on the capillary intersection area S is caused by the pressure variation Δp. It amounts to

$$F = S\Delta p = (\pi\phi^2/4)\Delta p. \quad (1)$$

The expression for the electromotive force in the electrical equivalent circuit results from the above relationship and from Equation 4 of [2] and Equation 3 of [5]:

$$E = [\phi/(4q)]\Delta p \quad (2)$$

where q denotes the charge density at the mercury–electrolyte solution interface. It results from the above equation and from Equation 1 [5] that the open-circuit voltage of the transducer output is independent of the frequency of the pressure variation Δp which acts on the open capillary end (Fig. 9) and is proportional to the pressure variation.

The open transducers to be used in the studies of model electrocapillary manometers were prepared as described in [4, 7, 8]. The usefulness of open electrocapillary elements in pressure measurements is limited to short-duration laboratory experiments only because of their instability caused by solvent evaporation, penetration of oxygen and of other impurities, and by salt precipitation at the inner surface of the capillary. All these inconveniences are absent in the construction used by us where the open capillary end is placed in a closed metal bellows (Fig. 10).

Pressure variation acting on the bellows modifies the internal pressure which in turn induces the displacement of the filling and the appearance of a voltage on the output terminals of the manometer.

The pressure variation inside the bellows is smaller than that outside because of the stiffness of the bellows. In the case where the variation in bellows length is small relative to its overall length, they are related by

$$\Delta p_{\text{out}} = \Delta p_{\text{in}}\left(\frac{16k_{\text{b}}V_{\text{b}}}{\pi^2\phi_{\text{b}}^4 p_{\text{in}}} + 1\right) \quad (3)$$

where Δp_{out} and Δp_{in} denote the pressure variations outside and inside the bellows, respectively, k_{b} the stiffness of the bellows, V_{b} the gas volume in the bellows including the gas volume at the capillary ends, p_{in} the pressure inside the bellows, and ϕ_{b} the bellows diameter.

Pressure jumps were applied by means of systems consisting of a manostat and a set of values. The system consisted of a glass flask connected through a three-way stopcock with a water manometer for the low-pressure range up to 4.4 kPa, or of a steel compressed-air bottle, a mechanical manometer and two electromagnetic slide-valves for CWUCh-Cieszyn for greater pressures up to 100 kPa. The rise time for the pressure applied in the system was 20 ms.

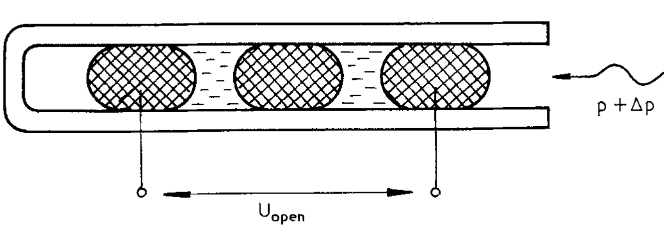

Fig. 9. Variable pressure electrocapillary manometer.

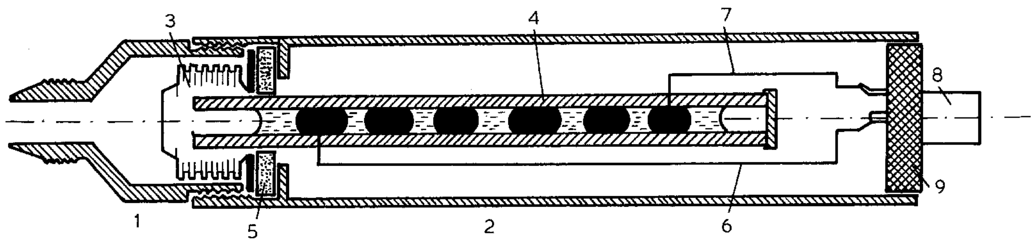

Fig. 10. Schematic diagram of electrocapillary manometer construction: 1, 2, manometer casing; 3, bellows; 4, electrocapillary transducer; 5, elastic gasket; 6, 7, output terminals of electrocapillary transducer; 8, output contact of elastic signal mounted on an insulating ring.

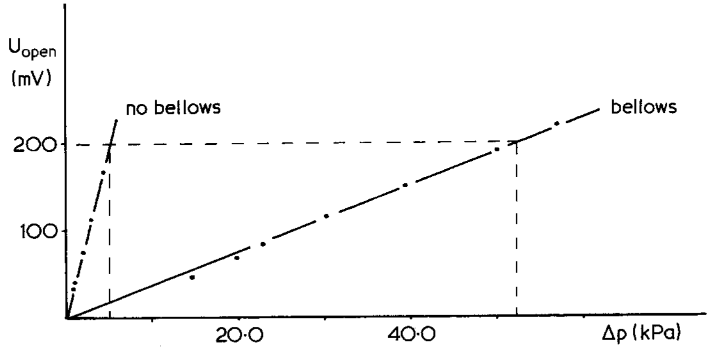

Fig. 11. Dependence of output voltage on the jump of pressure acting on the electrocapillary manometer.

The electrical output signal was fed to an oscilloscope or to a recorder through a voltage follower.

Fig. 11 presents a typical dependence of maximum open-circuit voltage on the pressure jump for a transducer with a bellows and one with no bellows. The construction parameters of the transducer were: number of interfaces, 20; inner capillary diameter, 0.37 mm; mass of the filling, 44 mg; and air column length, 8.65 mm. The bellows diameter was 8 mm and its stiffness $k_b = 22\ \mathrm{N\,cm^{-1}}$; the gas volume inside the bellows was 0.97 cm^3.

The $\Delta p_{out}/\Delta p_{in}$ value calculated from the above data by means of Equation 3 is 9.3; it agrees well with the experimental sensitivity ratio of the manometer with and without the bellows determined from the slopes of the lines in Fig. 11, which have a value of 10. The bellows reduces the pressure acting on the filling and extends the measuring range of the manometer, but at the expense of its sensitivity.

Electrocapillary manometers can be applied in numerous fields for measurement and for automation. They can be used for measurement and control of slowly-varying pressures and pressure jumps.

It should be stressed that the stability of electrocapillary manometers can be markedly improved by using the filling suggested in [6].

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