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Erkin Uljaev

Elyor Faxriddinovich Khudoyberdiev

Shohrukh Nurali o‘g‘li Narzullayev

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INVESTIGATION OF THE PARAMETERS OF SEMICYLINDRICAL CAPACITIVE SENSOR

Uljaev Erkin[1], Khudoyberdiev Elyor Faxriddinovich[2], Narzullayev Shohrux Nurali o'g'li[3]

[1]Tashkent State Technical University.
Address: 2 Universitetskaya st., 100095, Tashkent city, Republic of Uzbekistan.
E-mail: e.uljaev@mail.ru, Phone: +998999197164;
[2]Tashkent State Technical University.
Address: 2 Universitetskaya st., 100095, Tashkent city, Republic of Uzbekistan.
E-mail: elyor.faxriddinovich@gmail.com, Phone: +998977275527;
[3]Tashkent State Technical University.
Address: 2 Universitetskaya st., 100095, Tashkent city, Republic of Uzbekistan.
E-mail: narzullayevsh1993@mail.ru, Phone: +998909021716.

Abstract: *This study introduces a semicylindrical capacitive sensor, featuring an internal dielectric insulator, designed to measure moisture levels in bulk and other materials while in motion. The research employs numerical analysis to explore the sensor's capacitance variation and evaluate its performance. The change in capacitance of the semicylindrical capacitive sensor in the picofarad range is easily converted into a change in the frequency of the generator, which is implemented on an operational amplifier with feedback. The generator circuit is quite compact, and its output can be connected directly to the discrete input of a microcontroller without a matching element. Using the approximation method, taking into account the constructed formulas, a calculation was made, and a graph was constructed to illustrate the dependence of the change in capacitance of the semicylindrical capacitor on the change in the distance between the plates of the semicylinder. The measurement results fully confirmed the reliability of the theoretical outcomes.*
Keywords: *semicylindrical capacitive sensor, moisture measurement, flow, insulating material, dosing device, electrophysical dependence.*

Annotatsiya: *Ushbu maqolada ichki izolyatsion dielektrikka ega yarimsilindrik sig'im datchigi taqdim etilgan bo'lib, u oqimdagi sochiluvchan va boshqa materiallarning namligini o'lchash uchun ishlatiladi. O'zgarish xususiyatini tahlil qilish va yarim silindrsimon sensorning sig'imini hisoblash uchun raqamli tahlil usuli qo'llanildi. Yarimsilindrik sig'im datchigining sig'imini pikofarad diapazonida o'zgarishi teskari aloqa amaliy kuchaytirgichida ishlaydigan generator chastotasining o'zgarishiga osonlik bilan aylantiriladi. Generator sxemasi juda ixcham bo'lib, uning chiqishi muvofiqlashtiruvchi elementsiz mikrokontrollerning diskret kirishiga ulanishi mumkin. Tuzilgan formulalarni hisobga olgan holda silliqlantirish usulidan foydalanib, yarimsilindr plastinalar orasidagi masofa o'zgarishiga qarab yarimsilindrik kondensator sig'imining o'zgarishi hisoblandi va grafik chizildi. O'lchov natijalari nazariy natijalarning ishonchliligini to'liq tasdiqladi.*
Tayanch so'zlar: *yarimtsilindrik sig'im datchigi, namlikni o'lchash, oqim, izolyatsion material, dozator, elektr-fizik bog'liqlik.*

Аннотация: *В данной статье представлен полуцилиндрический емкостной датчик с внутренним изоляционным диэлектриком, используемый для измерения влажности сыпучих и других материалов в потоке. Для проведения анализа характера изменения и расчета ёмкости полуцилиндрического датчика был применен метод численного анализа. Изменение ёмкости полуцилиндрического емкостного датчика в пикофарадном диапазоне легко преобразуется в изменение частоты генератора, выполненного на операционном усилителе с обратной связью. Генераторная схема достаточно компактна, её выход без согласующего элемента можно подключить к дискретному входу микроконтроллера. Используя метод аппроксимации с учетом построенных формул был проведен расчет и построен график зависимости изменения ёмкости полуцилиндрического конденсатора от* *изменения расстояния между пластинками полуцилиндра. Результаты измерений полностью подтвердили достоверность теоретических результатов.*

Ключевые слова: *полуцилиндрический ёмкостной датчик, измерение влажности, поток, изоляционный материал, дозатор, электрофизическая зависимость.*

Introduction

The operational monitoring and regulation of the quality parameters of materials in the flow intended for subsequent processing, as well as decision-making for quality improvement, remain one of the pressing issues across all sectors of production. Examples of controlled materials include grains and grain products, the grain processing and flour production processes, flour-based products, selection and preparation of construction materials (sand, powders, etc.), production of various fertilizers, medicines, and so forth.

One of the first parameters controlled in most materials in flow is the moisture content of the material. To monitor moisture in flow, it is first necessary to determine the presence of the incoming controlled material, and then to conduct measurements. Various detection techniques exist for flow control, which vary depending on the type of material (bulk or liquid), its properties (magnetic sensitivity, electrical conductivity, viscosity, etc.), flow rate (slow or high), and so on.

Traditional devices such as flow meters [1], vortex flow meters [2], ultrasonic flow sensors [3], etc., are used to detect the presence of materials in flow. However, the manufacturing technologies and cost of modern devices are quite high. Moreover, such flow meters are not always suitable for use due to various objective and subjective reasons for both conducting and non-conducting materials.

Therefore, to overcome limitations related to material properties, simplify complex flow detection systems, and reduce implementation costs for the industry, it is necessary to apply an innovative method of flow measurement using the capacitive sensor probing method. The advantage of the selected method is that it allows simultaneous measurement of moisture and other parameters of various bulk materials.

Managing grain moisture is essential for numerous processes, including production and distribution. For instance, excessive moisture levels during storage and transportation can lead to mold growth [4]. On the other hand, if the moisture level is too low, the grain's quality can degrade. As a result, fast and non-invasive methods for detecting moisture content in grains are of utmost importance in grain preservation.

Practice has shown that the detection of material flow is easily performed with capacitive sensors, especially for liquid and bulk materials. Almost all flour mills, at the initial, intermediate, and final stages of production, conduct moisture measurements of the processed grain. At these stages, the amount of water added for moistening the grain is determined. However, due to the lack of devices designed for automated moisture control flow, their control is carried out in laboratory conditions using special drying devices. For moisture measurement of grain at each stage of production, moisture measurements of one set of samples are carried out by the arbitration method (using a drying oven), according to regulatory documents and standards. This process takes about 6 hours. Using the express method of measurement, considering sample collection and processed information handling, takes about 2 hours. The aim of this work is to develop the most optimal design of a capacitive transducer that will allow for the accurate and operational assessment of the moisture of bulk materials in flow and to investigate its electrophysical characteristics.

Research Methods and the Received Results

To date, for the measurement of moisture and other parameters of materials on a large scale, devices based on capacitive sensors of various designs are being used and developed, taking into account the conditions of operation, measurement accuracy, and properties of the measured medium [6]. In contrast to planar parallel and coaxial cylindrical sensors, research on cylindrical capacitive sensors has largely concentrated on examining electrostatic forces and nonlinear responses [7, 8]. A design of a semicylindrical capacitive sensor integrated with an interface circuit for measuring liquid flow in a stream was developed and analyzed in [9]. This type of sensor is predominantly used for monitoring and probing liquid materials in the flow. However, its use for measuring the moisture of bulk materials, due to their conductivity, both in stationary conditions and in flow, can lead to significant errors.

Experimental studies have shown that to reduce this problem, it is necessary to insulate the internal surfaces of the semicylinders. Analysis of the proposed design revealed that to date, no study has analyzed and discussed semicylindrical capacitive sensors with built-in dielectrics used for measuring the moisture of various bulk materials [10, 11]. Thus, this work presents a design of a semicylindrical capacitive sensor, including two metallized plates covered with a dielectric both inside and outside with a thickness of 2 mm, providing protection against mechanical and other damages. Polypropylene was chosen as the insulating material, as its physicochemical properties meet the requirements of our capacitive sensor.

To examine the electrophysical processes involved in moisture measurement of bulk materials, a numerical analysis method was applied, which calculates the capacitance of the semicylindrical capacitive sensor. Variations in the sensor's capacitance, occurring within the picofarad range, can be identified and converted into voltage changes via a high-frequency generator circuit, as illustrated in Fig. 1. This compact transforming circuit facilitates the efficient measurement of moisture in bulk materials. The effectiveness of this method has been validated through simulations conducted by Proteus PCB and MATLAB software.

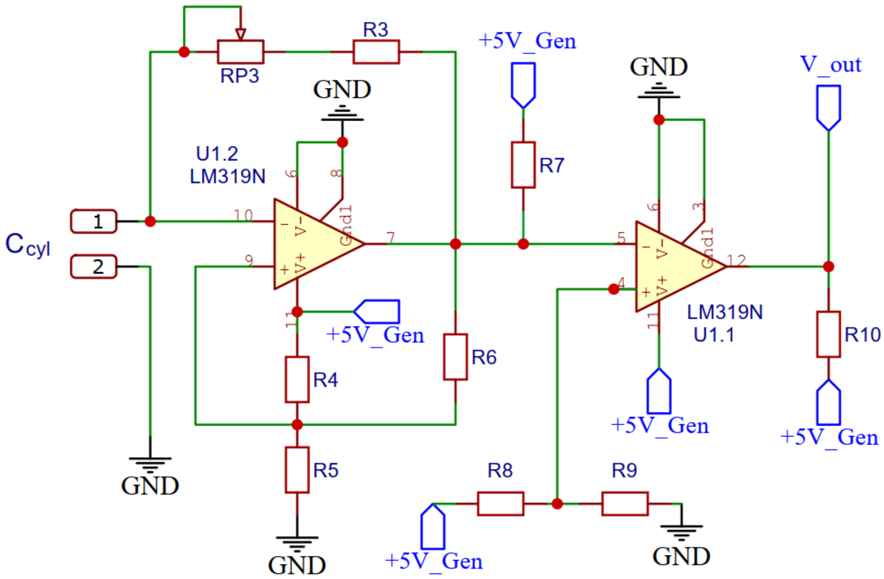
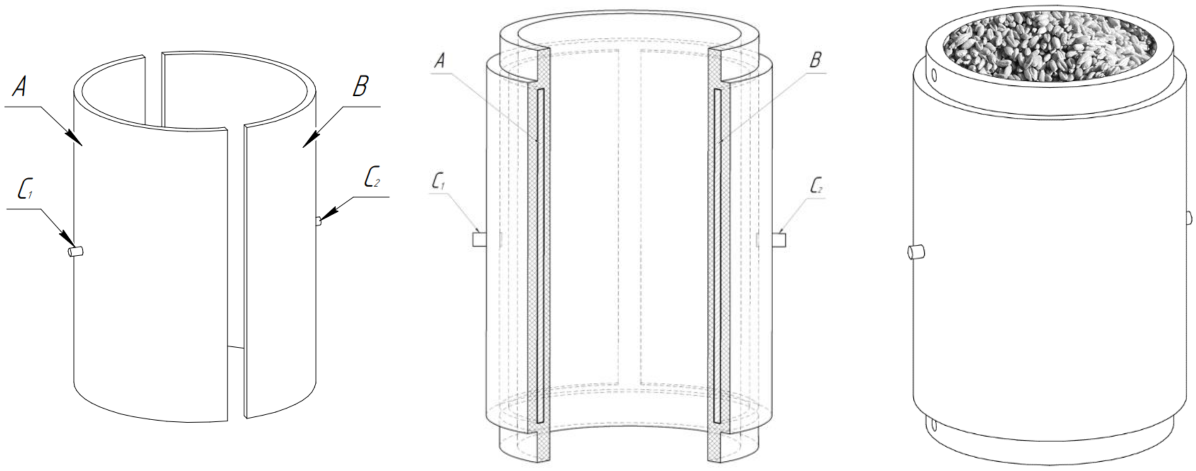


Fig. 1. ***Simulated schematic of the high-frequency generator.***

The results of the experiments [12], related to the measurement of moisture in bulk materials, fully confirmed the convenience of use, reliability, and accuracy of the semicylindrical capacitive transducer with a coating of dielectric insulating material, as well as the transforming circuit. This transducer allows for measuring the moisture of bulk materials in a range from 0.2% to 30% and above.

The main parameter of the semicylindrical capacitive transducer is its capacitance, which is determined by the distance between the electrodes, the shape and area of the semicylinders, the angle of the radii between the plates, as well as the electrophysical properties of the material and the dielectric permittivity of the used dielectric. Below are some theoretical justifications and conclusions of the formula for calculating the capacitance of the semicylindrical capacitive transducer, taking into account the mentioned parameters, presented in Table 1.

It is well-known that Maxwell's equations, which link electric and magnetic fields to charge density, are utilized to compute the capacitance of capacitive sensors. However, performing these analyses and calculations in such conditions can be highly complex, making it difficult to achieve accurate outcomes. To simplify this process, electrostatic analysis, a widely recognized approach, is often employed. This method helps reduce the complexity of the electric field caused by various charge distributions in materials with differing dielectric properties. The electromagnetic field inside a capacitive sensor can thus be treated as a stable electrostatic field [13]. Based on this electrostatic model, the capacitance variation of a semicylindrical capacitive sensor with an embedded dielectric is analyzed.



(a) *(b)* *(c)*

Fig. 2. ***General views of the capacitive sensor design:***
a) without insulating material; b) with insulating material (sectional view); c) with dielectric material.

Figures 2 (a), (b), and (c) display the general designs of the semicylindrical capacitive sensor with and without dielectric material. The semicylindrical capacitive sensor consists of two metallized semicylinders A and B, separated by a distance d. The electrode outputs for semicylinders A and B are denoted as C_1 and C_2, respectively [14, 15]. Figure 2 (b) shows two thin semicylindrical aluminum plates, coated with insulating material both inside and outside, with a wall thickness of t, providing reliable protection against mechanical and other damages. In the example shown in Figure 2 (b), air is used as the dielectric material with a dielectric permittivity of $\varepsilon_1 = 1$, and the insulating material (polypropylene) has a dielectric permittivity of $\varepsilon_2 = 2{,}2$. The dielectric permittivity of the bulk material shown in Figure 1 (c) is 5,4.

Before conducting the electrostatic analysis, let's first analyze and discuss the capacitance of two metal plates. In Figure 3, the capacitance is determined as [9, 15]:

$$C = \int_0^a dc = \int_0^a \frac{\varepsilon_0 \cdot a \cdot dx}{d + x\theta} = \frac{\varepsilon_0 \cdot \varepsilon_1 \cdot A}{d} \times \left[1 - \frac{a\theta}{d}\right] \tag{1}$$

where ε_0 is the permittivity of free space valued at 8.85 pF/m, ε_1 is the relative permittivity of the air, A is the area of one metal plate, and d is the minimum distance between the plates. Thus, if the number of slices of the semicylindrical capacitive sensor is large ($d \gg a\theta$), the capacitance in equation (1) can be approximated as:

$$C \cong \left[\frac{\varepsilon_0 \cdot \varepsilon_1 \cdot A}{d}\right]. \tag{2}$$

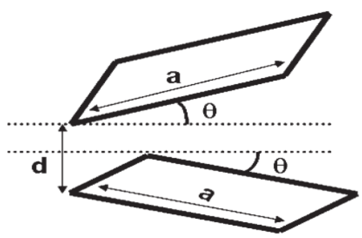
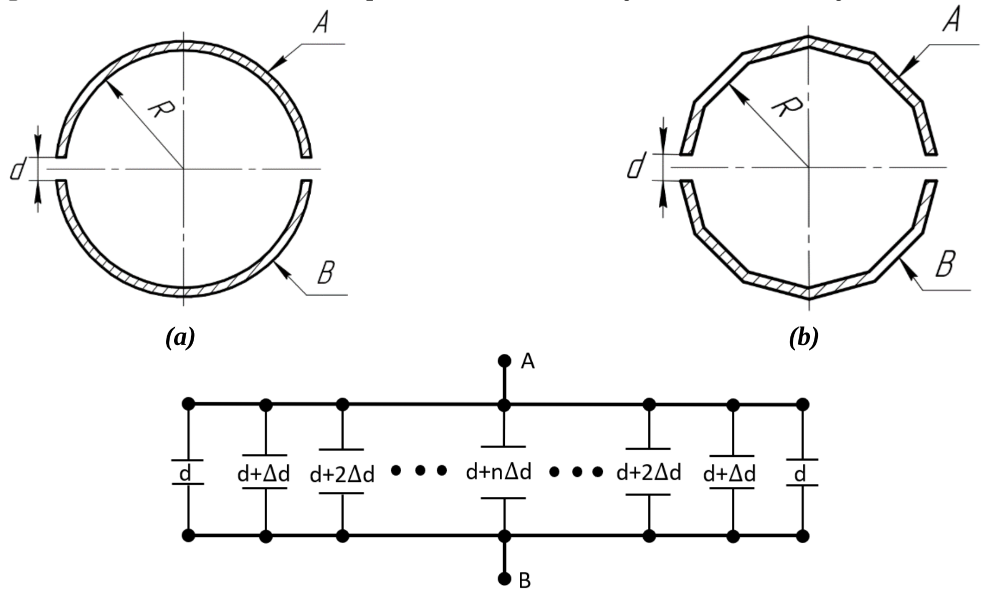


Fig. 3. ***Method of analyzing the capacitance of the semicylindrical capacitive sensor.***

It can be observed that the minimum distance between the two separated metal plates (d) will be the most significant factor in the subsequent numerical analysis of the semicylindrical capacitive sensor.



(c)

Fig. 4. ***Top-down view of the semicylindrical capacitive sensor without the dielectric-controlled material.***
a) Top view of the semicylindrical capacitive sensor without dielectric material; b) Approximate design of the semicylindrical capacitive sensor for investigation by numerical analysis method; c) Equivalent capacitors between terminals A and B, depending on the angle change (a).

Figure 4(a) presents a top-down view of the semicylindrical capacitive sensor without the dielectric-controlled material. The metallic semicylinders possess a radius R, with a minimum separation distance *d* between them. To analyze the change in capacitance of the semicylindrical capacitive sensor, the numerical analysis method proves to be the most efficient during the approximation process. The sensor's configuration for numerical analysis is illustrated in Figure 4(b). As depicted in Figure 3, each capacitor formed by the two metallic semicylinders can be modeled as a pair of metal plates separated by a distance Δd. Thus, all equivalent capacitors can be arranged in parallel between terminals A and B, as demonstrated in Figure 4(c). Given that the maximum radius of the semicylinder *R* is 27 mm, it is possible to set the number of approximation steps *n* depending on the segmentation step. We choose the number of approximations for the maximum and minimum radii to be four. According to physical laws, the capacitance between the plates decreases with an increase in the distance between them. Therefore, the equivalent capacitance scheme of the semicylindrical capacitor with an approximation number $n=4$ can be depicted as shown in Figure 4(c).

According to formula (2) and the presented figures, the capacitance of the two metallic semicylinders, considering the constant insulating material (dielectric) and without the controlled material, can be expressed as follows:

$$C_0 = \sum_{i=0}^{n} Ci(d+i\Delta d) = \varepsilon_0\varepsilon_1 2A \times \left[\frac{1}{d} + \frac{1}{d+\Delta d} + \frac{1}{d+2\Delta d} + \cdots + \frac{1}{d+(n-1)\Delta d}\right] + \frac{\varepsilon_0\varepsilon_1 A}{2R} = \\ = \sum_{i=1}^{n} \varepsilon_0\varepsilon_1 2A \times \left[\frac{1}{d+(i-1)\Delta d}\right] + \frac{\varepsilon_0\varepsilon_1 A}{2R} \qquad (3)$$

where ε_0 represents the permittivity of free space, with a value of 8.85 pF/m, while ε_1 denotes the dielectric permittivity of air. The variable *n* indicates the number of approximation steps used in the numerical analysis, *A* refers to the unit area of the metallic semicylinders, *d* is the minimum separation distance between them, and Δd signifies the increment distance.

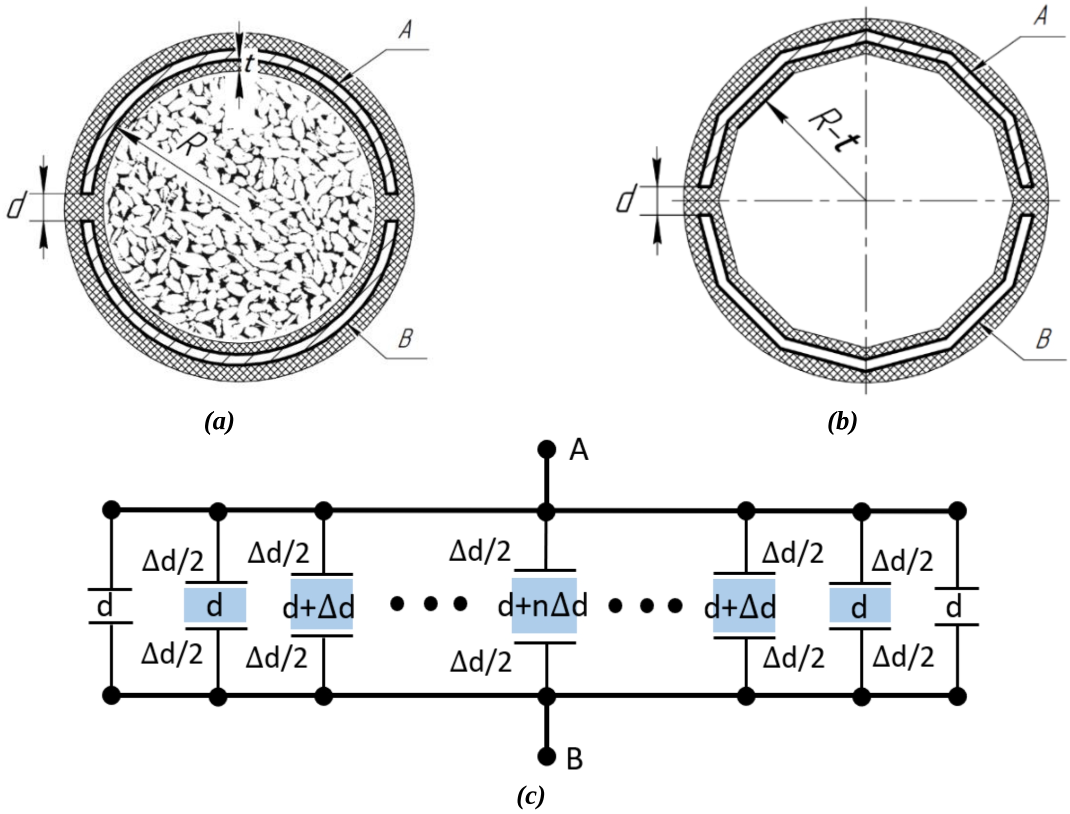


Fig. 5. ***Structure of the semicylindrical capacitive sensor incorporating dielectric material, which is analyzed using the numerical analysis method.***

(a) Top view of the semicylindrical capacitive sensor with a constant insulating dielectric and with dielectric material; (b) an approximate design of a semi-cylindrical capacitive sensor for conducting research using the numerical analysis method; (c) Equivalent capacitors between terminals A and B.

Similarly, Figure 5 depicts the structure of the semicylindrical capacitive sensor incorporating dielectric material, which is analyzed using the numerical analysis method. Following formula (3), the capacitance of the two metallic semicylinders with the dielectric bulk material is expressed as follows:

$$C_1 = \sum_{j=0}^{n} Cj(d + j\Delta d) = \varepsilon_0 2A \times \left[\frac{1}{\frac{d}{\varepsilon_2}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d}{\varepsilon_3}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+\Delta d}{\varepsilon_3}} + \cdots + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+(n-1)\Delta d}{\varepsilon_3}} \right] \quad (4)$$

$$+ \frac{\varepsilon_0 A}{\frac{2t}{\varepsilon_2} + \frac{2R-2t}{\varepsilon_3}} = \sum_{j=1}^{n} \varepsilon_0 2A \times \left[\frac{1}{\frac{d}{\varepsilon_2}} + \frac{1}{\frac{\Delta d}{\varepsilon_2} + \frac{d+(j-1)\Delta d}{\varepsilon_3}} \right] + \frac{\varepsilon_0 A}{\frac{2t}{\varepsilon_2} + \frac{2[R-(t+n\Delta d)]}{\varepsilon_3}}$$

where ε_2 is the dielectric permittivity of the insulating material, while ε_3 refers to the dielectric permittivity of the controlled bulk material. Thus, as outlined in formula (3), the capacitance of the semicylindrical capacitive sensor varies as the dielectric-controlled bulk material flows between the insulated metallic semicylinders, separate from the controlled material.

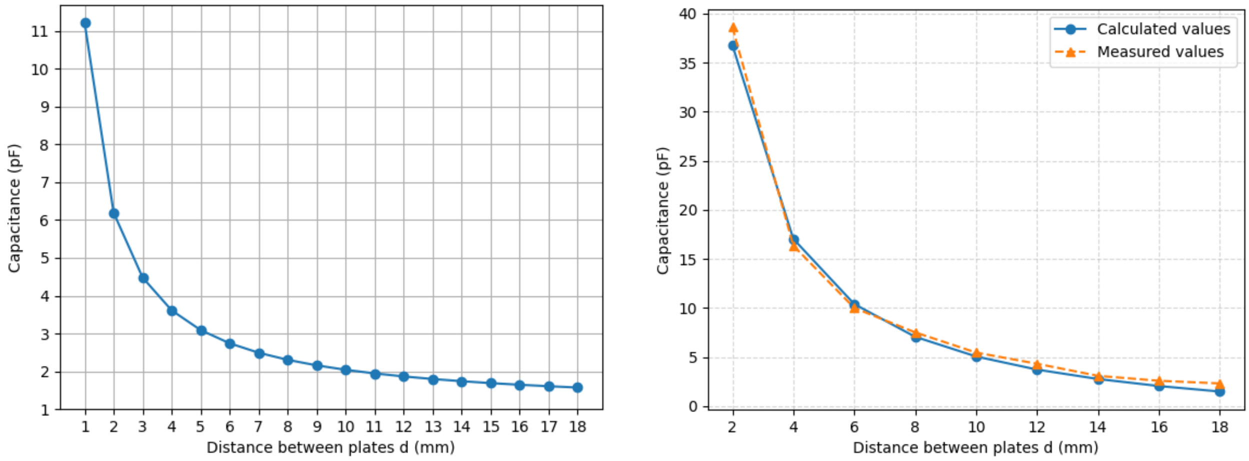
The calculations and capacitance measurements were carried out based on varying the distance between the sensor plates from 1 to 18 cm, which allowed us to determine the optimal value of this parameter.

Table 1 shows the initial data for calculating the dependence of capacitance on the capacitor plate spacing increment (for approximation).

Table 1.

Input data for the calculation

Parameter	Symbol	Values
Permittivity of free space	ε_0	8,85 pF/m)
Dielectric permittivity of air	ε_1	1
Dielectric permittivity of insulating material	ε_2	2,2
Dielectric permittivity of controlled bulk material	ε_3	5,4
Area of a single metal plate	A	0,006 м^2
Height of the semicylinder	h	78 mm
Distance between semicylinders	d	1-18 mm
Increment distance	Δd	h/n mm
Radius of the semicylinder	R	27 mm
Number of cuts	n	100
Thickness of the walls of insulating material	d'	2 mm



(a) *(b)*

Fig. 6. ***Graph of the dependence of the capacitance on the distance between the plates of the semi-cylindrical sensor:*** *a) calculation results without dielectric material; b) calculation results with dielectric material: Comparison of calculated and measured values.*

Fig. 6(a) shows a plot of capacitance versus plate spacing without considering the dielectric material. The graph illustrates the theoretically expected decrease in capacitance with increasing distance, obtained using formula (3). Analysis of the data presented in the graph of Fig. 6(b), showed that the calculated capacitance values obtained using formula (4) are very close to the experimental data measured with specialized measuring devices.

Conclusion

In the conducted study, based on the principles of electrostatic analysis of the interaction between electrodes, the changes in capacitance of a semi-cylindrical capacitive sensor with integrated dielectric were investigated. As a result of the analysis, a formula for calculating the capacitance between electrodes was derived. It is found that the key factor affecting the capacitance is the minimum distance between the separated metal plates, which is of particular importance for the subsequent numerical analysis of the device.

As part of the numerical analysis, each capacitor within the sensor is represented as a pair of separate metal plates separated by equal intervals of distance d. This allowed us to determine the number of approximation levels n depending on the chosen partitioning step. Based on these data, an equivalent capacitance circuit for a semi-cylindrical sensor was constructed and a formula was created to calculate its total capacitance, taking into account the internal insulating dielectric. The analytical study performed using the developed formula showed that the capacitance variation depending on the distance between the half-cylinders corresponds to the theoretical assumptions.

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