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Research Article

Tomasz Rymarczyk* and Jan Sikora

Applying industrial tomography to control and optimization flow systems

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Abstract: The flow control and optimization system based on industrial tomography is presented in this publication. Multiphase flow measurement technologies are still being built and improved. There is a clear tendency in the industry to implement more optimally related functions with an emphasis on active inspection and monitoring. Control methods include issues related to the processing of data obtained from various sensors located in nodes. Monitoring takes place within the scope of acquired and processed data and parameter automation. The main purpose of this work is to design a system for data acquisition and analysis by image reconstruction for various tomographic methods (resistive, capacitive, ultrasonic). The practical application of ultrasonic flow measurement to study gas emissions in the heat and power station chimney is presented

Keywords: Inverse problems, finite element methods, electrical tomography, ultrasound tomography, process tomography

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1 Introduction

This work concerns the idea of creating a solution for the architecture of tomographic sensors. The use of tomographic methods enables to manage the intelligent structure of the companies in terms of processes and products. This will enable the optimization and auto-optimization of design processes and production. Such solutions can operate autonomously by monitoring and controlling the measurements. Tomography includes many imaging techniques for the parameters of objects located in the research area [1–8]. The suggested approach is a model-based design and an evaluation process, where an optimization routine is used.

Industries, such as food, pharmaceuticals and petrochemicals, employ multi-phase flows in their processes. Phases in such processes include gas-solid, gas-liquid, and gas-liquid-solid. This is provided by different measurement techniques with quantitative local and global dynamic information of the flow, useful for system design and control. Multi-phase flow measurement technologies present practical challenges and continued progress is being made towards improving mentioned technologies [10]. The image reconstruction is obtained by solving the inverse problem that allows the imaging of processes [11–15].

2 Industrial tomography

Advanced automation and control of production processes play a key role in maintaining competitiveness. While costly technological equipment and production lines can be considered as the heart of industrial production, control systems and information technologies are its brain. They provide flexibility to quickly adapt production processes to change customer requirements and ensure safety and efficiency at the lowest possible cost of resources and energy. Hence, the development and application of advanced process control is one of the most effective levers for immediate and long-term gross energy savings, improved product quality, increased process safety and increased production flexibility, as well as ensuring security and promoting economic growth in conventional and emerging areas [16–24, 26].

Industrial tomography enables observation of physical and chemical phenomena without the need to penetrate inside. The tomographs allow us to "look inside" the tubes at the flow reactors. Tomography is a technique of imaging the interior of a tested object, based on measurements made on its edge. In order to obtain information about a test object, tomographs are used in various physical phenomena, in which information carriers are X-rays, gamma rays, ultrasound, electron beams, electric

***Corresponding Author: Tomasz Rymarczyk:** University of Economics and Innovation, Research and Development Center Netrix S.A, Lublin, Poland; Email: tomasz@rymarczyk.com
Jan Sikora: Research and Development Center Netrix S.A, Lublin, Poland; Email: sik59@wp.pl

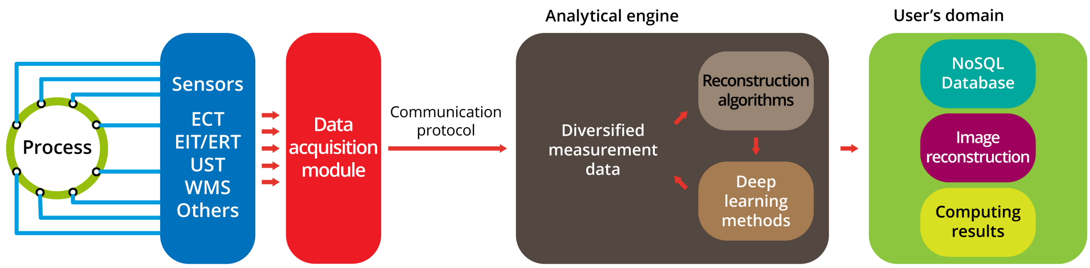

Figure 1: General measurement model for tomography sensors

currents, magnetic fields. The main advantage of the tomographic testing are non-invasive measurements in the tested environment, which do not change physical and chemical parameters that could interfere with the measurement results. Image reconstruction in industrial tomography is much more complicated than in medical tomography. The key parameters are the speed of analysis of the flowing raw materials and the accuracy of the reconstructed processes. The measurement must be fast, because some industrial processes run at high speed. The measuring system consists of a sensor, specialized electronics for capacitance measurement and data reconstruction and analysis system (see Figure 1). Tomography of industrial processes is a harmless, non-invasive imaging technique used in various industrial technologies. It plays an important role in the continuous measurement data, which allows better understanding and monitoring of industrial processes, providing fast and dynamic response, which facilitates real-time process control of fault detection and system malfunctions [27–30].

The idea of using a tomography to monitor industrial processes appeared in the nineties. Since then, various tomographic methods have appeared, including: electrical, magnetic, optical, ultrasonic, microwave and radioactive tomography. A common feature of all these techniques is the fast measurement speed. However, until now, it has not been possible to reconstruct the phase, flow velocity, temperature, pressure and distribution of chemical properties in real time. The recent development of intelligent massive parallel architectures at an affordable price now allows real-time data processing in a production environment. As a result, the tomography process can be transformed into a powerful sensor solution in the presented new concept of the system - control of processes based on tomography. This concept requires new data processing strategies and a correct extension of the classical control theory, because the latter is not sufficiently developed for a large amount of sensor data and must be created on a non-parametric criterion.

Industrial tomography applications are usually a challenge for obtaining spatial distribution data from observations that go beyond the process boundary. The biggest challenge is to achieve effective coverage of closed spaces using practical resources at a reasonable cost. Distributed infrastructure, such as operations and open processes, requires various tasks related to detection and start up, and is usually characterized by internal spatial organization. Sensor networks with feedback loops are the basic elements of production control (Figure 2). The decisive difference in the mass production of chemicals, food and other commodities lies in the fact that common process sensors only provide local measurements, *e.g.* temperature, pressure, filling level, flow rate or concentration of species. However, in most production systems, such local measurements are not representative of the entire process, therefore spatial solutions are necessary. Here is why the future belongs to the distributed sensors and imaging.

3 Measurement models

3.1 System idea

Stream monitoring in a substance flow is a new example in which wireless sensor networks (WSN) can provide remote monitoring, while CPS can be used to apply real-time information and analyse the underlying structure. Thanks to several available techniques for implementing the pipeline, all efforts consistently reflect the characteristics of the medium needed for transport, which depends on environmental, strategic and economic conditions. The intelligent delivery of flexible and reliable methods for tomography monitoring and detection technologies is at the heart of this section. Methods of substance pipelines distribution can be widely described on underwater, over ground and underground pipelines. Since leaks can be harmful to the environment, integral monitoring of pipelines is essential and must be reliable in real

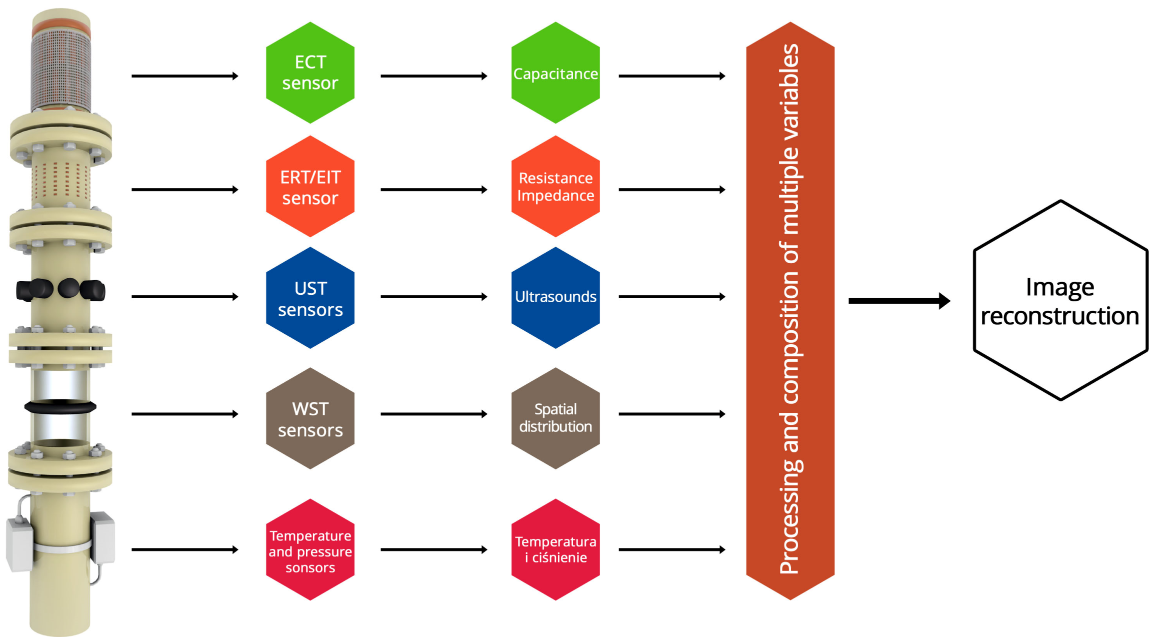

Figure 2: Idea of model sensors

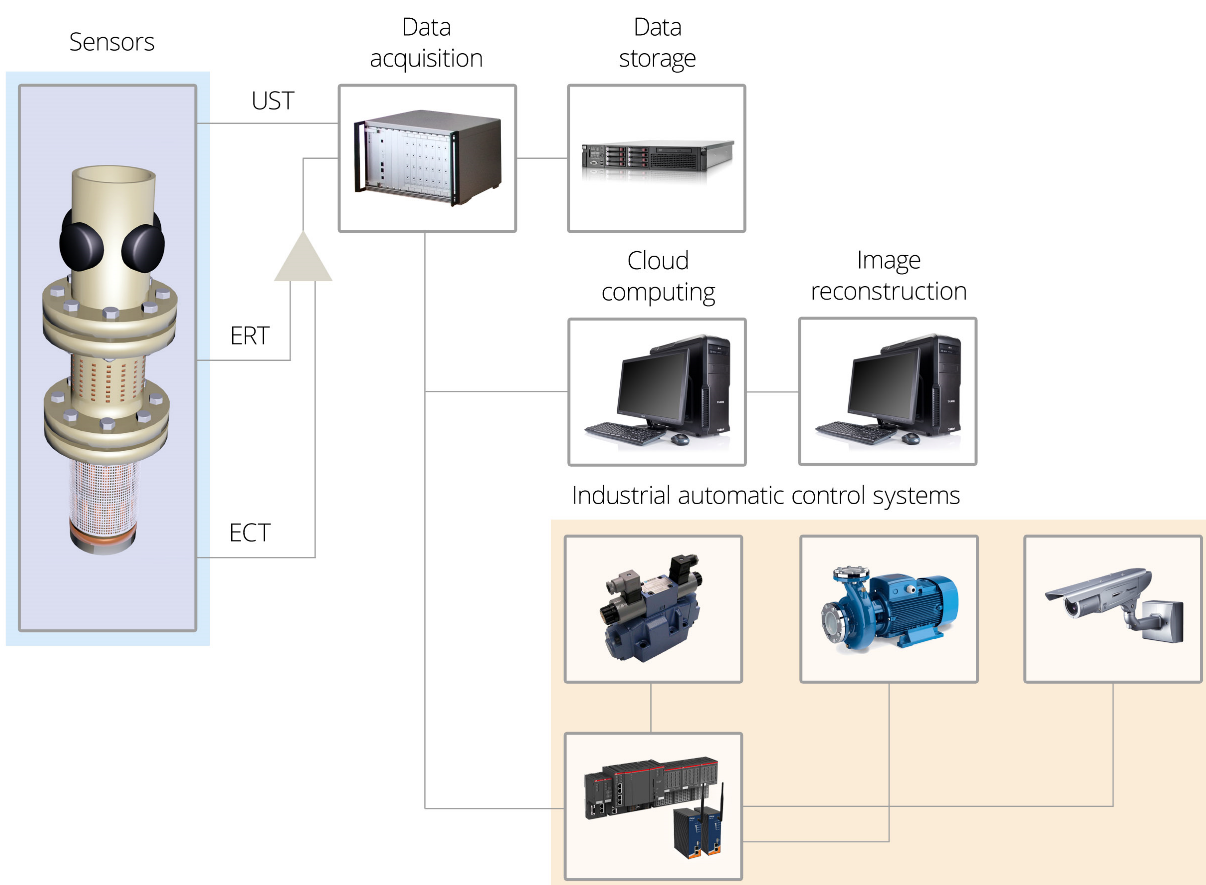

Figure 3: Data acquisition system

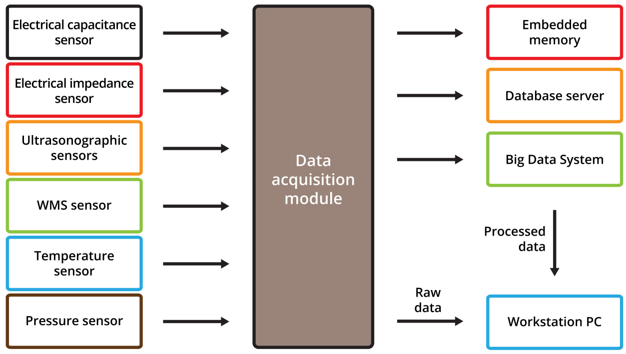

Figure 4: Complex system for the data acquisition, the image reconstruction with cloud computing model

time. The proposed model system (see Figure 3) includes resistance tomography (ERT) [31–33], electrical tomography (ECT) [34–36] and ultrasound tomography (UST) [37, 38].

Electrical tomography (ET) includes resistance tomography and capacitance tomography, which reconstruct the distribution of conductivity or permittivity of an object from electrical measurements. Ultrasound tomography is a technique that uses information contained in the ultrasound signal after it passes through the examined object. Complementary to the above methods may be wire mesh sensors (WMS) method by means of which it obtains the distribution of conductivity or permittivity in the flow of gas and liquid in a straightforward manner.

The type of sensors, their location and their use in the monitoring environment form the basis for topography monitoring systems. Placement of the sensor to monitor the pipeline can be classified as external placement and placement inside. The general model of a complex system for tomographic sensors is shown in Figure 4. Monitoring changes in pipelines by means of tomography can provide control of the industrial process through the visualization of two-phase flows. All tomography systems are non-destructive testing and monitoring methods.

3.2 Electrical resistance tomography

Electrical resistance tomography (impedance) is an imaging technique that uses different electrical properties of different types of materials. In this method, a power or voltage source is connected to the object, and then there are current flows or voltage distribution at the edge of the object. The collected information is processed by an algorithm that reconstructs the image. This tomography is characterized by a relatively low image of spatial resolution. Difficulties in obtaining high resolution result mainly from a limited number of measurements, non-linear current flow through a given medium and too low sensitivity of measured voltages depending on changes in conductivity in the area. The image reconstruction is very sensitive to the ubiquitous modelling errors, which are caused by inaccurately known auxiliary variables of the measurement model. In particular, the shape of the object is in practice always inaccurately known, and it has been shown that especially the errors in modelling shape produce severe errors.

The mathematical model is the inverse conductivity problem introduced by Calder'on

$$\nabla \cdot (\gamma \nabla \boldsymbol{u}) = 0, \tag{1}$$

where γ denotes conductivity, $\boldsymbol{u}$ represents electrical potential
or

$$\nabla \cdot ((\boldsymbol{\sigma} + i\omega\boldsymbol{\varepsilon})\nabla \boldsymbol{u}) = 0, \tag{2}$$

According to the ratio of $\omega\epsilon/\sigma$, when the resistance or the capacitance term is dominant, the governing equation is simplified further:

$$\nabla \cdot (\boldsymbol{\sigma}\nabla \boldsymbol{u}) = 0 \quad \text{for} \quad \frac{\omega\boldsymbol{\varepsilon}}{\boldsymbol{\sigma}} << 1 \;\; (ERT) \tag{3}$$

$$\nabla \cdot (\boldsymbol{\varepsilon}\nabla \boldsymbol{u}) = 0 \quad \text{for} \quad \frac{\omega\boldsymbol{\varepsilon}}{\boldsymbol{\sigma}} >> 1 \;\; (ECT) \tag{4}$$

where electrical resistance tomography (ERT) means the resistance, component is used for the tomography, while electrical capacitance tomography (ECT) used the capacitance component. Electrical tomography combining ERT and ECT is called electrical impedance tomography (EIT). It should be noted that frequently ERT is known as EIT.

A set of electric currents is injected into the object through these electrodes, and the resulting voltage is measured using the same electrodes.

Figure 5 presents the neighbouring (adjacent current method) of boundary potential data collection illustrated for a cylindrical volume conductor and 16 equally spaced electrodes: (a) first projection-1, (b) second projection-2.

3.3 Electrical capacitance tomography

Currently, in many industries it is necessary to monitor various technological processes. The visualization methods used (for example optical) do not allow full information about the nature of the process. Electrical capacitance tomography allows the observation of physical and chemical phenomena without the need to penetrate their interior. The source of information is the electrical capacitance between the electrodes placed on the perimeter of

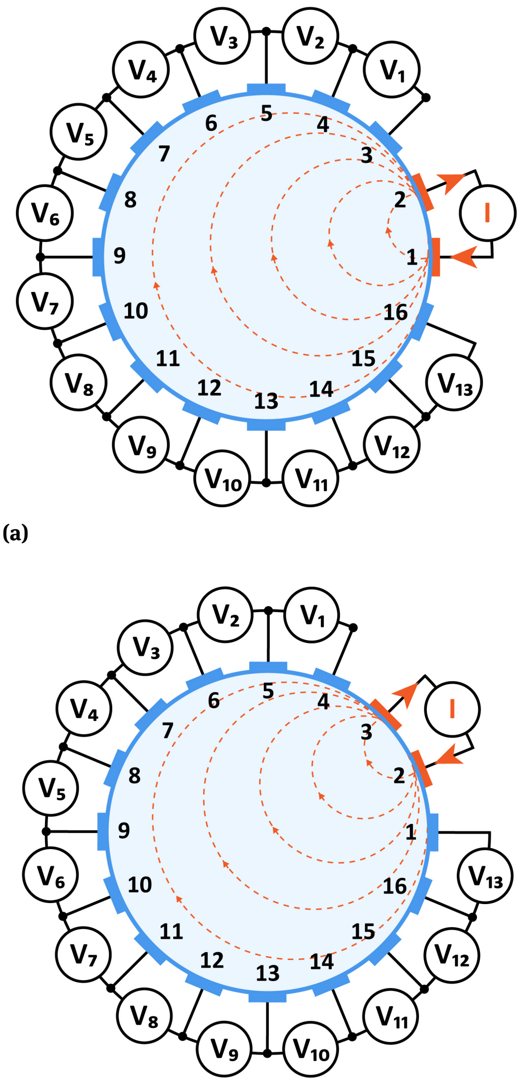

Figure 5: Neighbouring measurement method in ERT

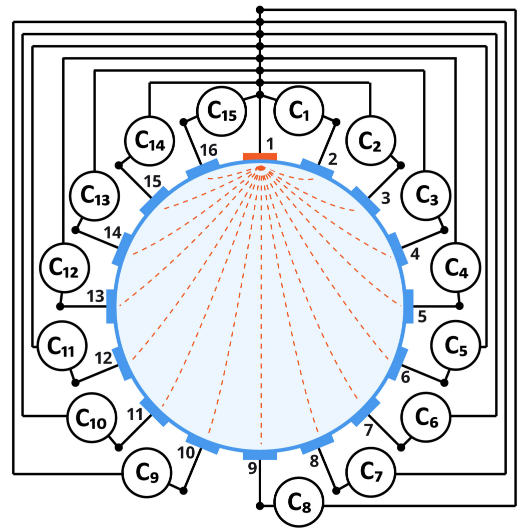

Figure 6: Measurement model of ECT

the measuring sensor. A very important feature of the measurement in the case of electric capacitive tomography is the lack of the need for physical interaction of the sensor with the tested medium, thanks to this method, which is non-invasive; that is, it does not interfere with the ongoing industrial process. Another advantage of this measuring technique is the quick acquisition of measurement data.

In the case of measurements in electrical capacitance process tomography, specially dedicated systems are used. Due to the difficult measurement conditions, it is not possible to use ordinary capacitance measurements. Industrial processes run at high speed, so the measurement must be fast. In addition, the measured capacities are of the order of femtofarad [36], which requires special techniques. The measuring system consists of a sensor, specialized electronics for measuring capacitance and reconstruction.

Measurements in ECT are carried out by determining the capacity between the electrodes placed on the edge of the object serving as capacitor electrodes (Figure 6). As a result of the inverse problem, a solution is obtained:

$$\boldsymbol{\varepsilon} = \boldsymbol{S} \cdot \boldsymbol{C} \tag{5}$$

where:
$\boldsymbol{\varepsilon}$ – permittivity matrix
$\boldsymbol{S}$ – sensitivity matrix
$\boldsymbol{C}$ – capacity matrix
The example of the Landweber algorithm:

$$\boldsymbol{\varepsilon}_{k+1} = \boldsymbol{\varepsilon}_k - \alpha \cdot \boldsymbol{S}^T \cdot (\boldsymbol{S} \cdot \boldsymbol{\varepsilon}_k \boldsymbol{C}_m) \tag{6}$$

where:
$\boldsymbol{\varepsilon}_{k+1}$ – permittivity matrix, current iteration
$\boldsymbol{\varepsilon}_k$ – permittivity matrix, previous iteration α – coefficient
$\boldsymbol{C}_m$ - measured capacity matrix
Visualization of the interior of the examined body is obtained on the basis of registered capacity measurements. These permeability distributions can be directly related to the material concentration present in the sensor space (probe).

3.4 Ultrasound tomography

Measurement methods using information contained in the ultrasonic signal after passing through the tested medium are called ultrasound transmission methods (Figure 7). The main advantage of tomographic examinations is non-invasive measurement in the tested environment, which does not cause changes in physical and chemical parameters that could interfere with the measurement results. Ultrasonic waves, as they belong to short waves, have propagation and radiation properties, so that ultrasounds like rays can be treated. The lengths of these waves depend on the medium and are in the range from a few micrometres in liquids to several dozen centimetres in metals. They can be used to measure the damping coefficient and the time of ultrasonic signal transition in the medium subjected to their influence. In addition, multiple measurements can be made with the help of ultrasound without fear of damage or irradiation of examined objects. The measurement of such parameters as the time of signal transitions, damping factor and its derivative by frequency enable, after appropriate reconstructive transformations, the imaging of the internal structure of the tested medium as well as flow parameters: its speed, average velocity or velocity profile. Differences in the local values of specific acoustic parameters are the basis of this imaging. The image obtained by appropriate reconstruction methods presents the distribution of local values of selected acoustic parameters (obtained from measuring data by scanning technique from as many directions as possible after the ultrasonic pulses have passed through the tested environment). This technique allows obtaining quantitative images of the internal structure, in which numerical values of each pixel describe such physical properties of the examined objects as *e.g.* temperature distribution, density or viscosity.

Problem of image construction in case of the ultrasonic or radio tomography very often leads to the overdetermined algebraic set of equations, which can be expressed in the matrix form:

$$\boldsymbol{W}\boldsymbol{f} = \boldsymbol{s} \tag{7}$$

where: $\boldsymbol{W}$ is the matrix of dimensions $m \times n$ and $m > n$, $\boldsymbol{s} = [s_1, s_2, \ldots, s_m]^T$ – right hand side vector (one column matrix), and $\boldsymbol{f} = [f_1, f_2, \ldots, f_n]^T$ – the solution vector.
One of the ways of the solution of the problem (7) is to find the vector $\boldsymbol{f}^*$, which minimize Euclidean norm of residual vector $\boldsymbol{r}$ for the known matrix $\boldsymbol{W}$ and vector $\boldsymbol{s}$:

$$\|\boldsymbol{r}\|_2 = \min \|\boldsymbol{s} - \boldsymbol{W}\boldsymbol{f}\|_2, \quad \left\|\boldsymbol{f}^*\right\|_2 = \min \|\boldsymbol{f}\|_2 \tag{8}$$

where the last minimum is taken for all vectors $\boldsymbol{f}$, which fulfill the previous relation. The equation (8) is well known as a Linear Least Squares Problem (LSP).

To calculate the solution to the Problem LS and analyze the effect of data errors as they influence to the solution of LSP, we will use the Singular Value Decomposition (SVD) theorem. This theorem says that for any arbitrary matrix $\boldsymbol{W} \in R_{mxn}(m \geq n)$of rank k exist an $m \times m$ orthogonal matrix $\boldsymbol{U} \in R_{mxm}$, an $n \times n$ orthogonal matrix $\boldsymbol{V} \in R_{nxn}$ and an $m \times n$ rectangular matrix of singular values $\boldsymbol{D} \in R_{mxn}$.

$$\boldsymbol{W} = \boldsymbol{U}\boldsymbol{D}\boldsymbol{V}^T \tag{9}$$

$$\boldsymbol{D} = \begin{bmatrix} d_1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & d_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_{k-1} & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & d_k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & d_n \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix} \in R_{m\times n} \tag{10}$$

where: $d_1 \geq d_2 \geq \ldots \geq d_{k-1} \geq d_k > d_{k+1} = d_{k+2} = \ldots d_n = 0$, but k is known as a pseudo rank of matrix $\boldsymbol{W}$.

The elements d_i of the matrix $\boldsymbol{D}$ are called the singular values of the matrix $\boldsymbol{W}$. The Eq. (9) represents Singular Values Decomposition of matrix $\boldsymbol{W}$. Knowing decomposition (9) it is a straightforward way to find out the solution of the linear Least Square Problem (LSP):

$$\boldsymbol{f}^* = \boldsymbol{W}^+\boldsymbol{s} = \boldsymbol{V}\boldsymbol{D}^+\boldsymbol{U}^T\boldsymbol{s} \tag{11}$$

where: matrix $\boldsymbol{W}^+ = \boldsymbol{V}\boldsymbol{D}^+\boldsymbol{U}^T$ is called the pseudo-inverse matrix to the given matrix $\boldsymbol{W}$ and the matrix $\boldsymbol{D}^+$ could be calculated in the following way:

$$\boldsymbol{D}^+ = \operatorname{diag}\left(\tfrac{1}{d_1}, \quad \cdots \quad \tfrac{1}{d_k}, \quad 0, \quad \cdots \quad 0\right) \in R_{n\times m} \tag{12}$$

In computed tomography normally, one must deal with bad conditioned matrix coefficients of the Eq. (11).

In case of ill – conditioned problem the solution can be achieved in the following way. Suppose the singular value decomposition is computed for the matrix $\boldsymbol{W}$:

$$\boldsymbol{W} = \boldsymbol{U}\begin{bmatrix} \boldsymbol{D}_d \\ \boldsymbol{0} \end{bmatrix}\boldsymbol{V}^T \tag{13}$$

where $\boldsymbol{D}_d$ is a diagonal matrix containing singular values. The difference between matrices $\boldsymbol{D}$ and $\boldsymbol{D}_d$ is that the last one is the square matrix dimension $n \times n$.

4 Image reconstructions

4.1 Methods of image reconstruction

From a mathematical point of view, industrial tomography also belongs to the inverse problems of the electromagnetic field. The inverse problem of electromagnetic field is

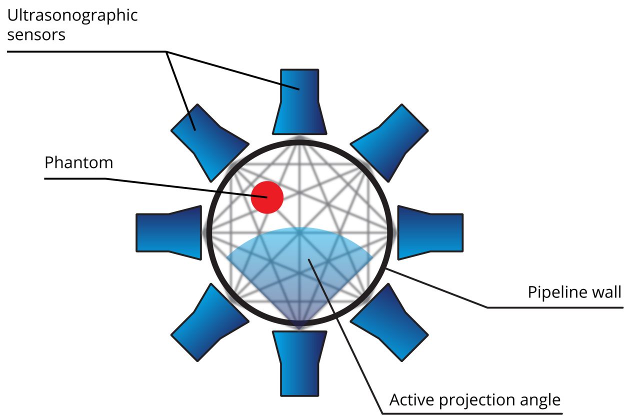

Figure 7: Idea of UST measurement model

called the process of identification, optimization or synthesis in which the parameters describing a given field are determined based on the possession of some information specific to this field. Inverse problems are difficult to analyse. As a rule, they do not have unambiguous solutions and are badly conditioned [32]. The reason for this is often too little or too much information, which is sometimes contradictory or linearly dependent. The numerical analysis of the problem is carried out using, among others, the finite element or boundary element method. In the case of data shortages, we talk about under determined problems, and in the case of excess, about over determined problems. Knowledge of the a-priori process can make image reconstruction more resistant to incomplete or damaged data. Automatic data analysis has always been an important part of the diagnosis of the process based on tomography. The basic step is the size of the reconstructed image, for example conductivity or permittivity, acoustic impedance, dielectric loss to the parameters of a physical process (phase embolism, density, temperature, humidity, type of concentration). A more advanced analysis leads to the feature extraction. Examples are bubble size measurement [30], interface detection [29] or mixing time estimation [30].

4.2 ECT

The purpose of the study was to obtain measurement results for various phantom configurations. The consequence of this action is both a practical verification of the quality of the individual solutions (also observing differences between them) and the same numerical package itself. The forward problem was solved using the finite element method [10]. Grids used in calculations: rare 2 218 nodes and 4 146 finite elements, dense 7 861 nodes and

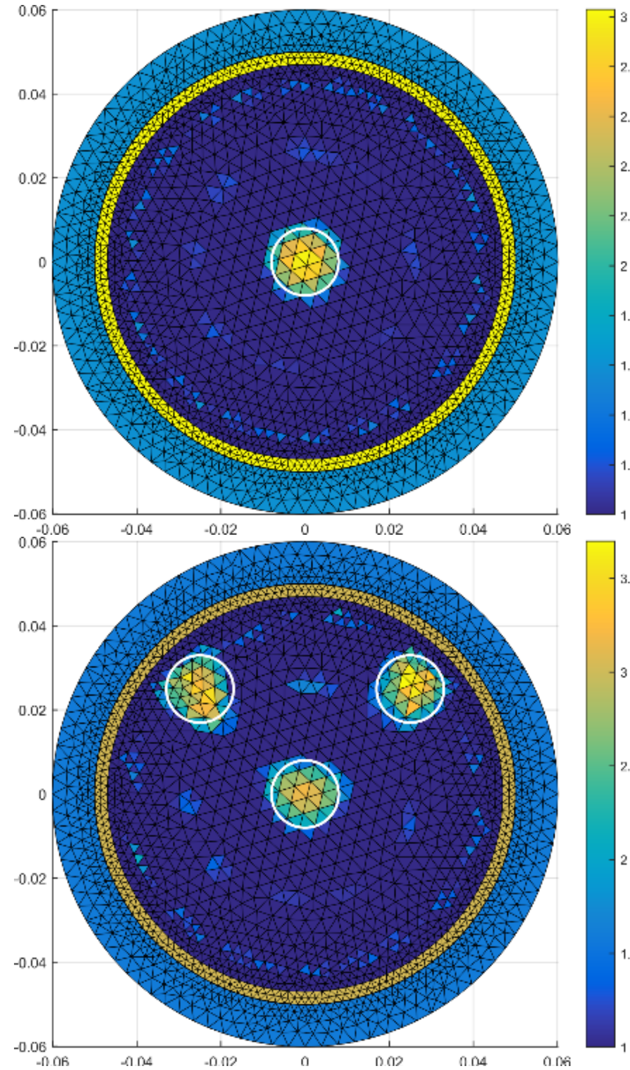

Figure 8: ECT – the example of the image reconstruction

15 146 finite elements. The example of the image reconstruction is shown in Figure 8 for the simulation and the real image reconstruction by the ECT device measurement. The Levenberg-Marquardt method was used to solve the inverse problem.

4.3 ERT

In the example shown in Figure 9, the Total Variation method was used for image construction [1]. A mesh of finite elements has been generated inside the area. Input data to the algorithm is the result of voltage measurements between neighbouring voltage electrodes. The algorithm is solving for such a distribution of conductivity, so that the values of inter-electrode voltages calculated on its ba-

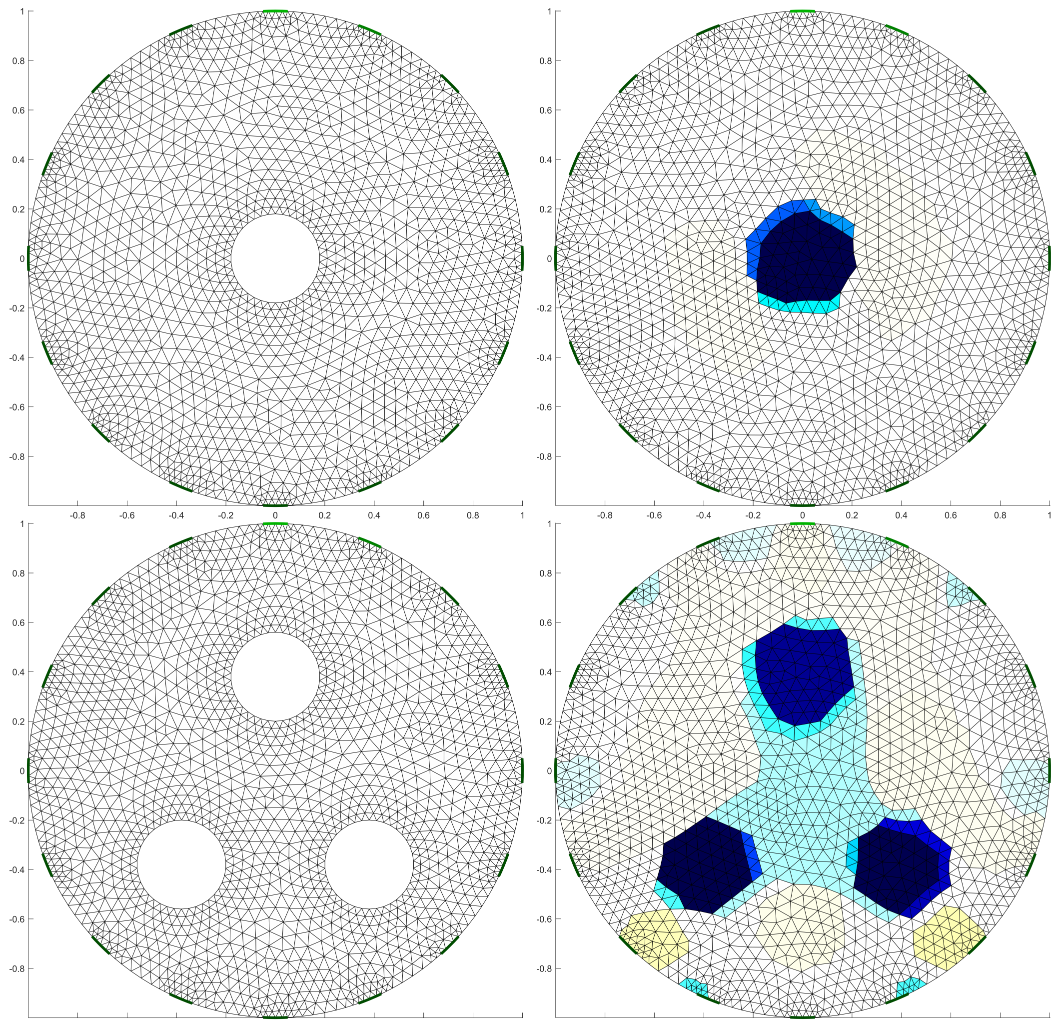

Figure 9: Image reconstruction: by Total Variation method

sis are as close as possible to the measuring values of these voltages.

4.4 UST

The numerical experiment was carried out on synthetic data and noisy data. The image construction algorithm was designed in such a way that an overdetermined system of equations could be generated, *i.e.* one for which the number of equations is greater than the number of unknowns. Unfortunately, the immanent feature of the tomography, among other things, is that the matrix of coefficients is a rectangular matrix pseudo-rank deficient. In such cases the trial solutions should be considered [37, 38] and only one of them could be selected. Images of the experiments for various objects (square and rectangle) are shown in Figures 10–11.

The obtained results are a raw picture of tomographic imaging for synthetic data. In the presented numerical experiments, no additional regularization method was used to obtain images without streaks. Despite this, it can be concluded that the results obtained by the proposed method are a faithful representation of the modelled objects and enable their precise location within the considered area.

5 Application

5.1 Idea

The tomographic measuring methods (such as ECT, ERT, UST) are mainly used where non-contact flow measurement of clean, contaminated, chemically aggressive liquids and high-pressure liquids is required. Ultrasound

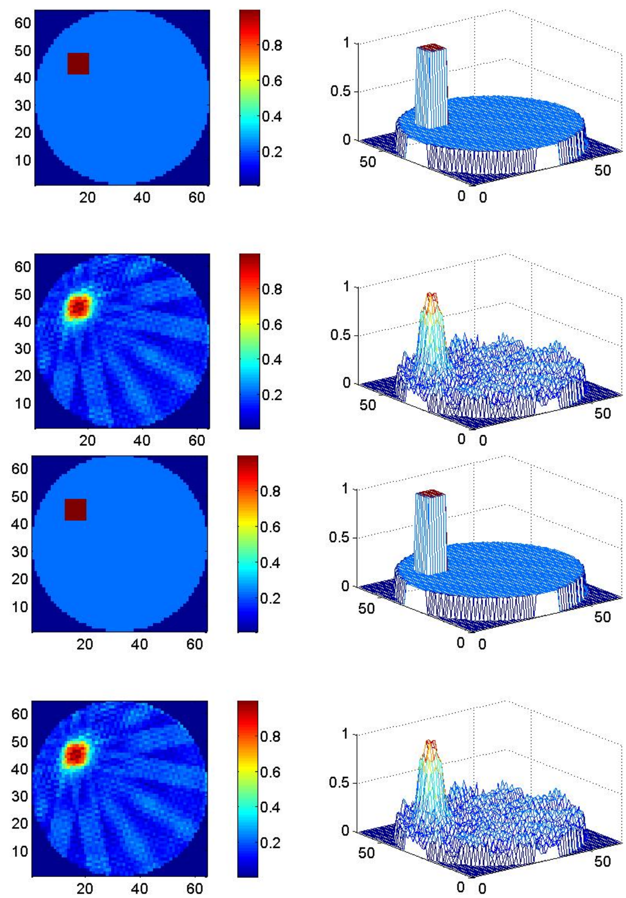

Figure 10: Square shape model and its tomographic profile

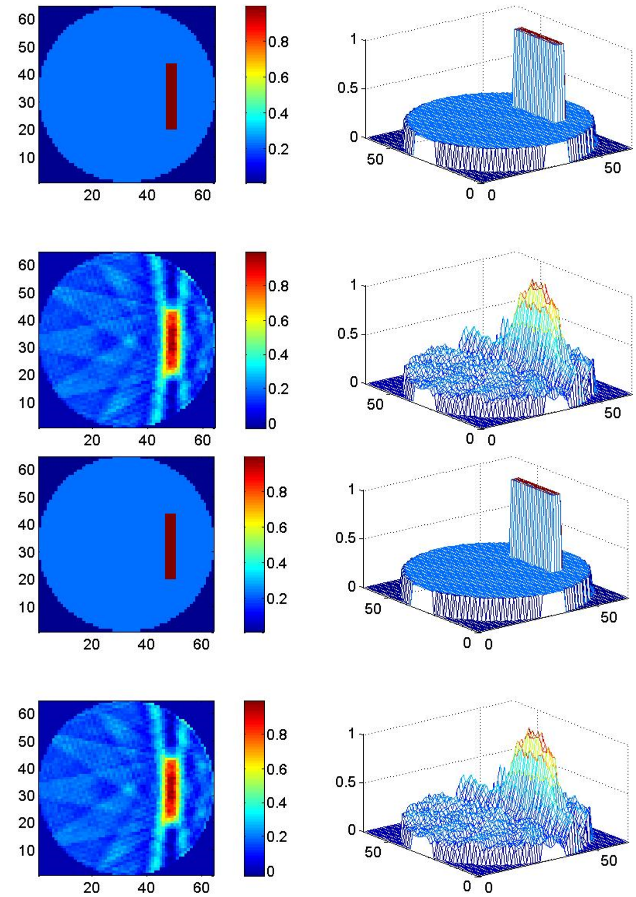

Figure 11: Model of the "rectangle" object and its tomographic profile

covers a wide range of applications, installation of water and wastewater in the industrial processes. An important and at the same time unique advantage of the ultrasonic flow meter is the possibility of mounting it on any measuring section, on the outside of the duct, pipeline, etc. Thus, it is possible to install the device not only on a new, but also existing and modernized point of the pipeline at any time. It is not required - which is a big advantage of the flow meter - to interrupt or at least reduce the pressure in the pipe during the installation of the device. The use of non-invasive sensors mounted outside the pipeline enables constant measurement of the flow of chemically aggressive liquids. This method also avoids, among others, pressure loss in the pipeline. Ultrasonic sensors can be, in some situations, assembled with special straps or chains to the outer surface of the pipe. The flowmeter can be used on pipelines of various diameters and practically on all types of materials such as plastic, carbon steel or cast iron with cement or hard rubber. Many models of flowmeters allow flow measurement also in flexible pipelines. The necessary condition for the use of the flowmeter is the acoustic permittivity of the material of the pipeline.

Due to the design, ultrasonic flowmeters are also used to measure the flow velocity in pipes with incomplete filling. There are also models of flowmeters, which are used for flow measurement in open channels and gravity flow pipes.

Another application is the measurement of volumetric flow or mass non-conductive liquids. It is widely used in the petroleum, chemical and pharmaceutical industries. From the point of view of flow measurement, liquids with a conductivity below 1-50 [μS/cm] are generally considered as non-conductive liquids. Such liquids include: oils and mineral fuels, solvents, demineralized water and boiler water. Volumetric flow measurement is a financially beneficial solution, ideal for pipelines with large diameters or for high pressure applications.

Many types of flowmeters are used as control devices in water treatment and sewage treatment plants, in technical and ventilation gas distribution systems, in the production of electricity, paper and chipboard production, cement production, waste utilization and many other branches of the industry.

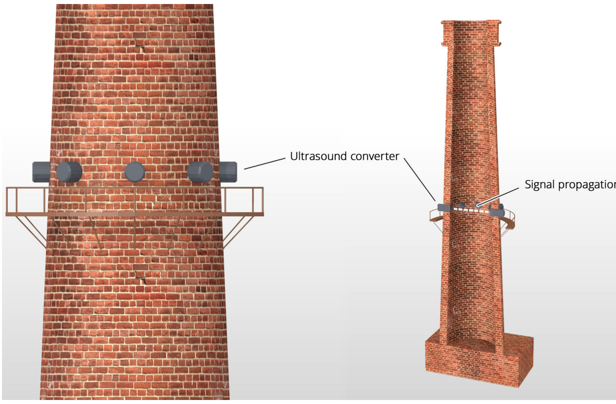

Figure 12: Application of the ultrasonic flow measurement method for testing gas emissions in the chimney of a heat and power plant

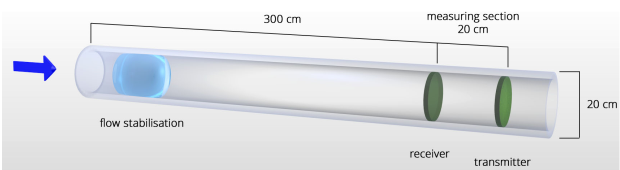

Figure 13: Multi-path ultrasonic flowmeter

Due to increasingly stringent modern safety requirements, ecology and economics, modern technologies seek accurate and inexpensive means of measuring the flow of gases, vapours or liquids, mixtures of two-phase and solids, both in pipes and pipelines with large and small diameters as well as closed channels (see Figure 12).

The use of single-track ultrasound flowmeters is useful, especially due to ecological requirements, in monitoring emissions of *e.g.* gases and particulates discharged in heat and power plants by chimneys into the atmosphere. In this type of tests, in addition to the flow velocity, a continuous measurement of changes in the temperature field $\boldsymbol{T}$ of the flowing medium is used according to the following dependencies:

$$\boldsymbol{C}_s = \frac{\boldsymbol{L}}{2}\left(\frac{\boldsymbol{t}_2 + \boldsymbol{t}_1}{\boldsymbol{t}_2 \cdot \boldsymbol{t}_1}\right), \quad \boldsymbol{T} = \boldsymbol{r} \cdot \boldsymbol{C}_s^2 \tag{14}$$

where: $\boldsymbol{C}_s$ - velocity of ultrasound wave propagation in the inspected medium, $\boldsymbol{r}$ - correlation coefficient considering the composition and structure of the medium examined.

5.2 Multitrack flowmeter (tomographic)

In order to increase accuracy flowmeters are built, which have more ultrasonic transducers: transmit - receive. These are so-called multi-path ultrasonic flowmeters. Figure 13 shows a model of such a flow meter.

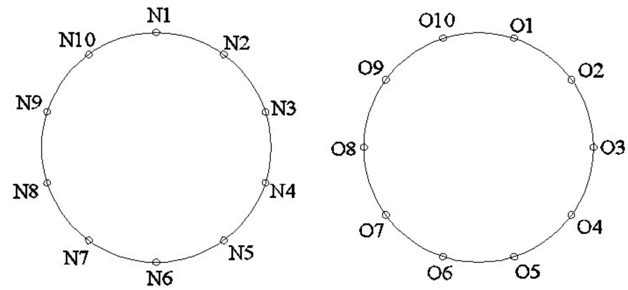

Figure 14: Distribution of transmitting and receiving transducers

In the system considered by us, a distribution of sensor sets around the pipe was assumed in two planes perpendicular to the pipe axis. Operating frequency of transducers is 40 [kHz], whereas the diameter of the pipe 20 [cm]. The receiver's surface is located at a distance of 300 [cm] from the beginning of the pipe, and the plane of the transmitters is located 20 [cm] from the plane of the receivers. The mentioned distance creates the so-called a measuring part on which the flow velocity is measured.

Before the measurement, the tested medium is stabilized by a system of adhering thin tubes (flow conditioner). This is done so that the flow is the same throughout the pipe and only takes place in the axial direction, and the velocity has a constant value. It has been assumed that the transmitters generate ultrasound waves with relatively low frequencies, and then the spreading angle of the beams of such waves is large enough and allows them to reach all receivers located on the circumference of the pipe. The distribution of transmitters and receivers is shown in Figure 14. The values of beam crossing time are collected on the measurement section according to the measurement protocol shown in Figure 15 (axonometric projection).

Figure 16 shows the same protocol, parallel to the orthogonal projection of the viewport perpendicular to the pipe axis and the direction of projection parallel to the axis of the tube.

Transmitters are started sequentially from the first to the last one. They generate ultrasonic pulses that reach all receivers with different delays. The times of these waves are the basis for calculating the average value of the velocity of the tested flow. Figure 17 shows all measurement paths between the plane of the transmitters and the plane of the receivers in two views: axonometric (a) and perpendicular (b).

In order to determine the speed value as accurately as possible, it is necessary to mathematically estimate the average velocity value $\boldsymbol{V}_r$, for example by introducing integrated weighting factors $\boldsymbol{V}_i$, in accordance with the rela-

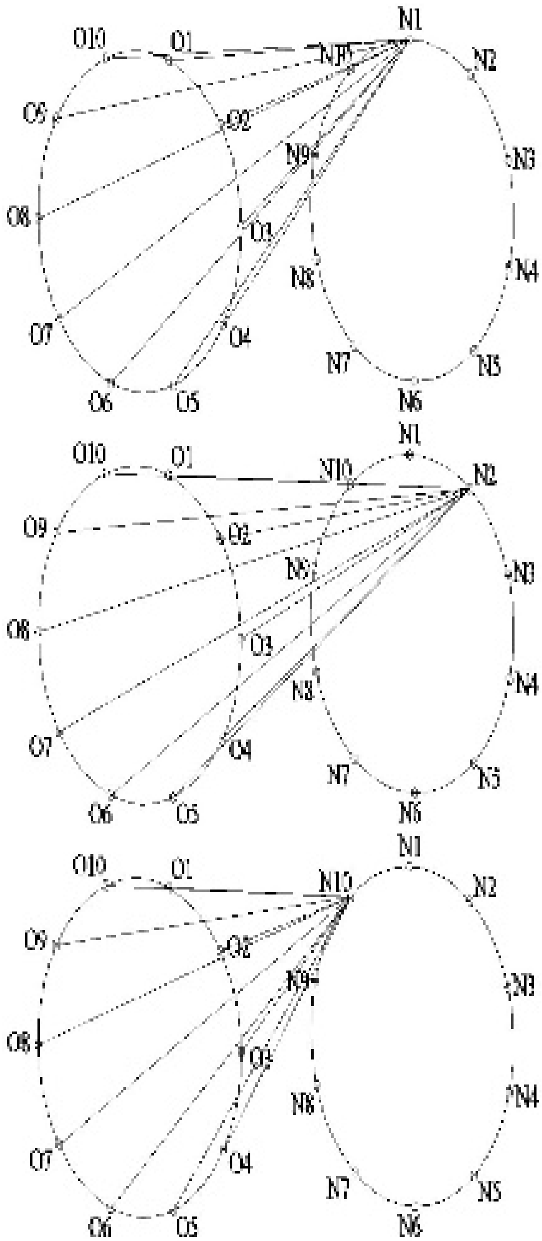

Figure 15: Measurement report - axonometric projection

tionship:

$$V_r = \sum_{i-1}^{n} w_i V_i \qquad (15)$$

where V_i is the speed value from the ***i***-th measuring path, and w_i is the weighting factor of the ***i***-th measuring path.

The average value of the flow velocity is insufficient to correctly determine the flow throughout the pipe cross-section. A relatively complex image of the velocity distribution in the tested pipe cross-section is required. The image of the velocity distribution in a plane perpendicular to the direction of the flow can be obtained by ultrasonic

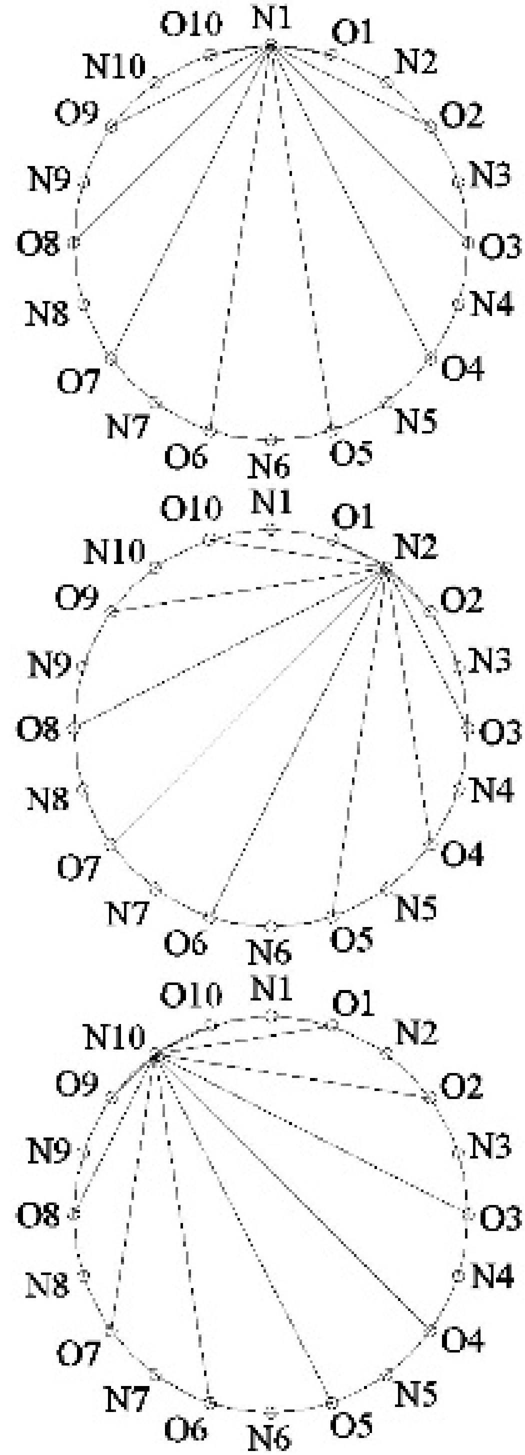

Figure 16: Parallel to the orthogonal projection of the viewport perpendicular to the pipe axis and the direction of projection parallel to the axis of the tube

tomography. After the appropriate processing of the measurement results of the velocity vectors of the flowing particles, the fields of velocity vector distribution profiles, that

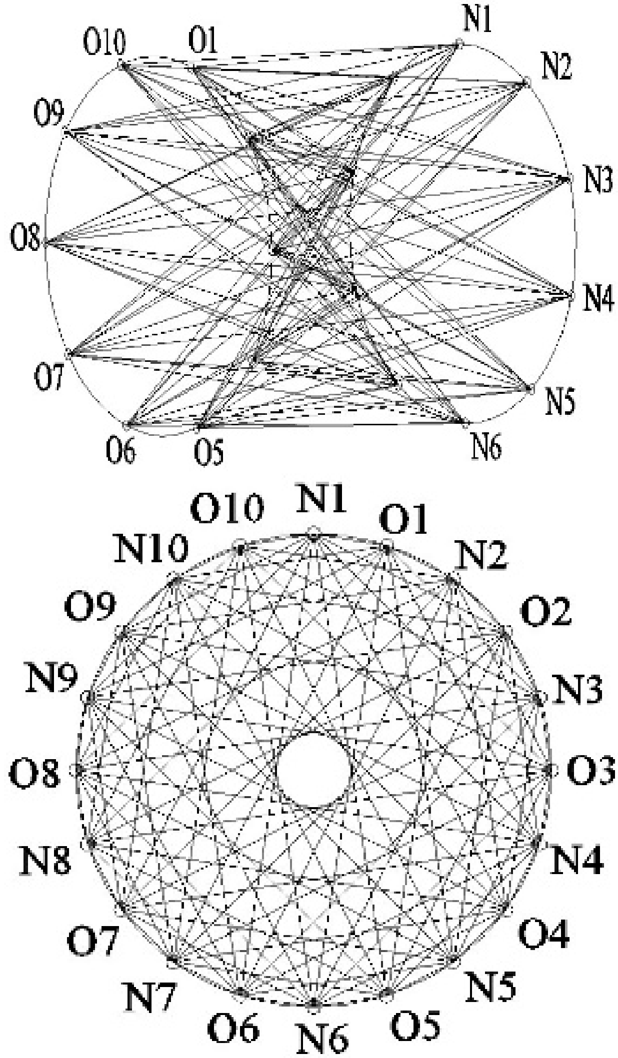

Figure 17: All measuring paths between the transmitter plane and the receiver plane a) axonometric view, b) orthogonal view

change over time, can be obtained (in a given pipe section).

Flowmeter multitrack transmitting and receiving transducers, arranged as shown in Figure 17, are called tomographic ultrasound flowmeters, which enable to get an image of the velocity distribution of the ultrasonic wave in the test medium.

5.3 Tomography visualization methods for monitoring processes

Given the growing demands of ecology and security, there is a need for more accurate and cheaper ways to monitor the gas flow that can be used in applications. This type of research is becoming more important in the case of frequently used gas systems that use hydrocarbons, as well as hydrogen, which in the case of depletion of petroleum resources, is considered to be the most likely fuel for internal combustion engines or fuel cells used in vehicles in the nearest future. The use of tomography may be an alternative (in relation to the currently used) method for such monitoring methods. Ultrasonic flow measurements are among the most promising.

The main advantage of this method is the fact that it is based on non-contact, non-invasive flow measurement, which does not cause any pressure or other physicochemical changes in the observed environment. Multi-path systems with various sets of transmitters and receivers are used to increase data and accuracy of measurement. In the system under consideration, equally spaced sensors are arranged around the circumference of the pipe in a perpendicular surface to the axis of the pipe.

In the analysed system, transmitters generate ultrasonic pulses (one after the other), which reach all receivers with different delays. The duration of these waves is the basis for calculating the average value of the measured flow velocity. In the presented case, the algorithm of algebraic reconstruction techniques (ART) was used.

6 Conclusion

This work presents the idea of a flow control and optimization system based on tomographic sensors. Electrical tomography and ultrasound tomography are included. The presented reconstructions were obtained by solving the inverse problem that allows the imaging of processes. The model of application of ultrasonic flow measurement method to study gas emissions in the heat and power station chimney was presented. Industrial tomography can analyse physical and chemical phenomena without the need to penetrate the inside of the object. A new research will set mathematical foundations using formalisms to determine, analyse, verify and validate systems that monitor and control physical objects and entities. The new infrastructure will benefit different economic and industry sectors. Sophisticated design tools capture the dynamics of system engineering. The application structure includes a communication interface, unique optimization algorithms and data analysis algorithms for image reconstruction and process monitoring. The development of new systems based on electrical and ultrasound tomography can greatly improve the production process at various stages. In our numerical experiment, calculations using 2D modelling were applied. The obtained results are satisfactory, and further research could bring the answer on whether the proposed method will find practical application. In the future study it is very important to develop optimal algorithms to solve the inverse problem for accurate and fast processes imaging. For this purpose, statistical and computational intelligence algorithms will be used.

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