Технічні науки

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REAL-TIME ACTIVE ONLINE MONITORING SYSTEMS IN LEATHER MANUFACTURING PROCESSES

Integrated Real-Time Active Online Monitoring Systems and Technological Features of Their Production and Operation in the Leather Industry

Summary. *A real-time active online monitoring system for leather manufacturing processes is presented, fully tailored to the specific requirements of the leather industry. The system employs contactless resonance sensors as a key component, integrated across all stages of hide processing—from soaking (used to remove preservatives, dirt, and blood), liming, hair removal, and deliming to tanning (including vegetable tanning), dyeing, fatliquoring, drying, and finishing.*

The importance of continuous parameter monitoring in the "dead zones" of technological tanks is highlighted, along with the design of the sensor module (a sleeve with a solenoid coil) and its manufacturing methods, including the application of RITM technologies.

The paper outlines approaches to integrating the sensors into the production line and discusses the anticipated benefits: improved uniformity of hide processing and final leather quality, reduced defect rates through timely detection of deviations, and automatic real-time adjustment of processing modes according to raw material properties.

Key words: *Active monitoring, Automated production, Contactless sensor technology, Technological operation features, Ideal final result, Advanced*

leather manufacturing, RITM technologies, Specialized technological equipment, Level of dynamic activity.

Introduction. Leather manufacturing involves a multi-stage technological process that is highly sensitive to deviations in parameters at each step. From hide preparation (soaking and washing) to the final finishing of leather, all operations—including liming, hair removal, deliming, tanning, dyeing, fatliquoring, drying, and more—must be conducted under strictly controlled conditions to ensure uniform material processing.

Even minor disruptions to the processing regime—such as fluctuations in temperature, pH, reagent concentration, or humidity—can result in uneven hide treatment, surface defects, or variability in the properties of the finished batch. Traditional monitoring systems in the leather industry are often limited to periodic sampling and laboratory analysis or indirect control methods (e.g., based on processing time), which do not guarantee optimal product quality.

In recent years, there has been a growing trend toward the implementation of automated sensor systems capable of continuous, real-time monitoring and regulation of process parameters.

Modern tanning drums equipped with temperature, humidity, and pressure sensors allow for automatic tracking of technological operations and timely adjustment of parameters. This ensures that each batch of leather consistently meets high-quality standards.

One promising direction is the use of contactless resonance sensors—devices capable of remotely sensing changes in physical parameters of the environment or material without direct exposure to aggressive media. These sensors can detect changes in dielectric permittivity, electrical conductivity, or other properties influenced by variations in substance concentration, moisture content, temperature, and more.

Resonance sensors are particularly well-suited for leather production environments, which often involve aggressive substances (such as alkalis, acids used in deliming and tanning, and organic dyes) and feature enclosed, hard-to-access, or hazardous process tanks. Such conditions are incompatible with traditional wired sensors and active electronics, making a contactless data acquisition strategy the optimal solution. This approach enables the remote measurement of variables such as viscosity, temperature, and pressure using passive sensors placed in sealed or hazardous zones.

Resonance sensors provide this capability: when embedded in the wall of a processing tank or equipment, they allow for the collection of necessary data via electromagnetic interaction—without direct contact with the measured environment.

This article explores the application of contactless resonance sensors for continuous monitoring of all key stages in the leather processing workflow. It justifies the need for constant parameter tracking even in hard-to-reach "dead zones" of production equipment, outlines the design and integration features of the sensors, and analyzes the expected improvements in leather quality and production efficiency following the implementation of such a system.

Problem Statement

Non-Uniform Processing in "Dead Zones"

One of the major challenges in leather manufacturing is ensuring uniform processing of raw hides across all areas of technological vessels and equipment. Large drums, vats, and other reactors often contain zones with limited mixing—so-called "dead zones"—where process parameters such as reagent concentration, pH, or temperature deviate from the average values in the bulk volume. For example, during soaking or pickling (acid treatment prior to tanning), more concentrated or more diluted solutions may accumulate locally near the walls or in the corners of tanks.

Traditional monitoring methods, which rely on sampling from a single location (typically the center of the vessel), fail to detect these deviations in dead zones. As a result, some hides may receive insufficient treatment (under-tanned or under-dyed), while others may be overexposed (over-limed, overdried, etc.), leading to increased defect rates or intra-batch variability in quality.

This problem is especially critical during tanning and dyeing stages, where uneven distribution of tanning agents or dyes can cause staining, inconsistent coloration, and variable strength properties in the final leather. Similarly, during drying after fatliquoring, localized moisture accumulation due to insufficient air circulation can cause uneven drying, resulting in variations in thickness and residual moisture across different areas of the hides.

Overall, the lack of data on local process conditions reduces process controllability and hinders full automation, as the control system cannot compensate for internal parameter gradients.

A second key aspect of the problem is the variability of raw materials. Hides arriving for processing may differ significantly in terms of thickness, collagen fiber density, fat content, and contamination level. Even hides from the same animal species (e.g., cattle) can require different processing durations and reagent dosages for optimal results.

In current practice, technologists are forced to apply average or excessive chemical dosages and process durations "with a margin" to ensure proper treatment of even the least responsive material. This approach results in reagent overconsumption, increased load on wastewater treatment systems, and, in some cases, degradation of leather quality—over-processing due to excess chemical exposure can irreversibly damage the material during tanning.

The absence of automatic adjustment mechanisms for incoming material properties means that the control system fails to account for batch-specific characteristics of hides, further increasing the risk of defects.

Thus, the problem statement is as follows:
To develop a continuous active monitoring system capable of real-time tracking of key parameters at all stages of leather manufacturing—including in potentially

problematic dead zones—and automatically adjusting processing modes based on real-time sensor readings and the specific properties of the raw hides.

Solving this problem requires the implementation of a multi-point sensor monitoring system integrated into the overall process control framework. The scientific and technical challenge lies in selecting sensor devices and placement methods that enable reliable, contactless parameter control within aggressive environments, while also providing sufficient response speed and durability for operation in a closed-loop control system.

Methods

Approach to Active Online Control

The proposed active online control system consists of a network of distributed sensor modules installed at various stages of the technological process and a centralized automated process control system (APCS). The sensors continuously measure local process parameters (temperature, pH, chemical concentration, humidity, etc.) and transmit data in real time to the controller. Control algorithms analyze the incoming data and compare it with predefined process curves (recipes tailored to specific types of raw materials).

Upon detecting deviations, the system automatically adjusts the process settings: for example, by regulating reagent dosages (acid feed during liming, tanning extract during tanning, dye during coloring), mixing or drum rotation intensity, medium temperature (including heating or cooling), or the duration of the processing stage.

This creates a closed-loop control system: sensors → controller → actuators, which is the essence of active control.

Contactless resonant sensors are the key element of this system, ensuring reliable sensor operation in aggressive and hard-to-reach environments without requiring direct contact with chemical reagents. These sensors operate based on the principle of resonance in an oscillatory circuit, where one of the elements is an inductive coil (solenoid). The frequency and quality factor (Q) of the resonant circuit are sensitive to changes in the electromagnetic properties of the surrounding medium.

If the coil is placed, for instance, adjacent to the wall of a tanning drum or (safely) immersed in solution, changes in the dielectric constant or electrical conductivity of the medium will shift the resonance frequency and alter the amplitude-phase characteristics of the circuit. By tracking these shifts using an external excitation and signal-receiving unit, one can remotely infer the medium's parameters.

In essence, this type of sensor functions similarly to a radio-frequency humidity or concentration sensor, with the medium acting as the resonator's load. Thanks to the contactless signal reading scheme (no electrical connection between the sensor and the external measurement unit, interaction occurs via an electromagnetic field), the sensor remains sealed and chemically resistant, and it can be installed in moving or sealed equipment (e.g., on a rotating drum or inside a closed vat).

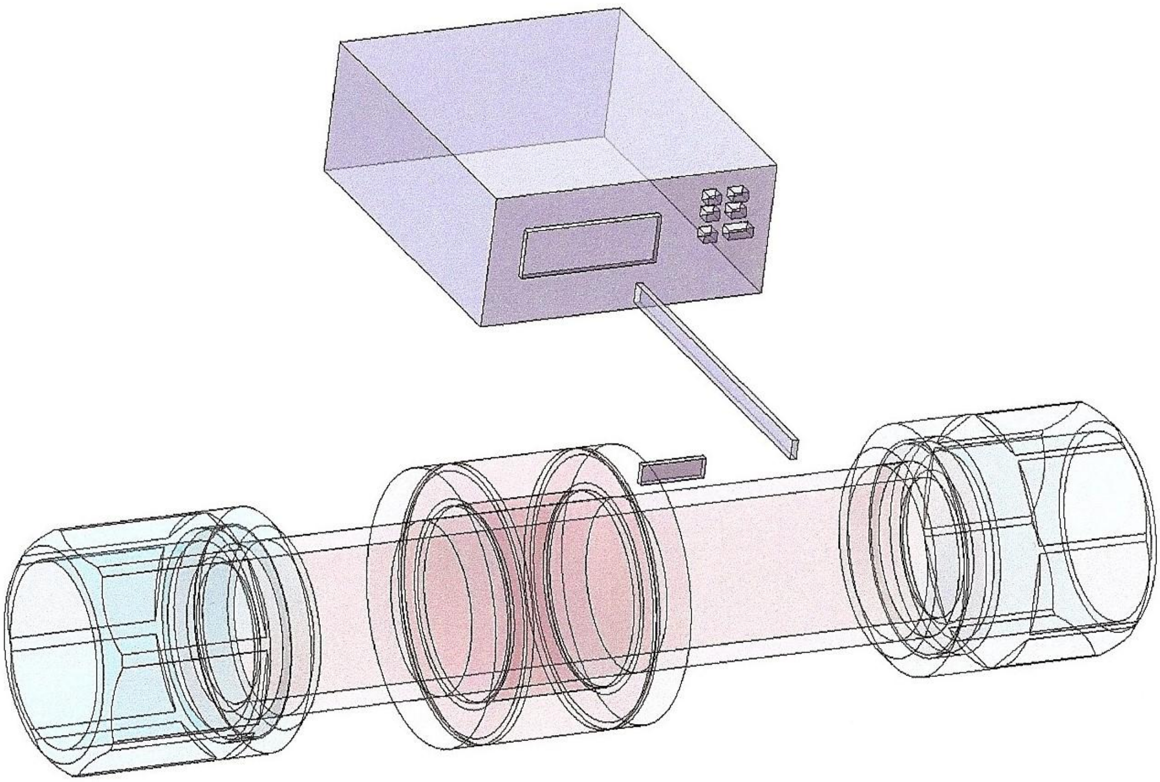
Data acquisition is performed by an external generator/receiver of radio-frequency signals. This unit can be implemented as a separate module mounted outside the apparatus, opposite the sensor location. In the simplest setup, each sensor module is tuned to a specific resonant frequency and is periodically irradiated by the external generator within a predefined frequency range. By registering the frequency of peak response (resonance) and its shifts, the system calculates the changes in the monitored parameter.

A more advanced option involves active sensors with built-in electronics: in this case, the sensor coil is connected to a miniature transmitter that sends data wirelessly (e.g., via LoRaWAN, Bluetooth Low Energy, or passive RFID) to the central controller. However, active sensors require a power source or battery, which may not be ideal in the environment of a tanning drum.

Therefore, preference is given to passive resonant sensors, which do not require an internal power supply—these are the types intended for use in the proposed system. Such passive sensors can remotely measure physical quantities (viscosity, temperature, pressure, etc.) even in hazardous zones, allowing all sensitive electronics to be located outside the aggressive environment.

Moreover, advanced designs of passive sensors can utilize the external electromagnetic field not only for data retrieval but also for wireless power transfer to the sensor module (via inductive or radio-frequency coupling). This opens the door to the development of fully sealed "maintenance-free" sensors with virtually unlimited operational lifespan.

Design and Fabrication of the Sensor Module



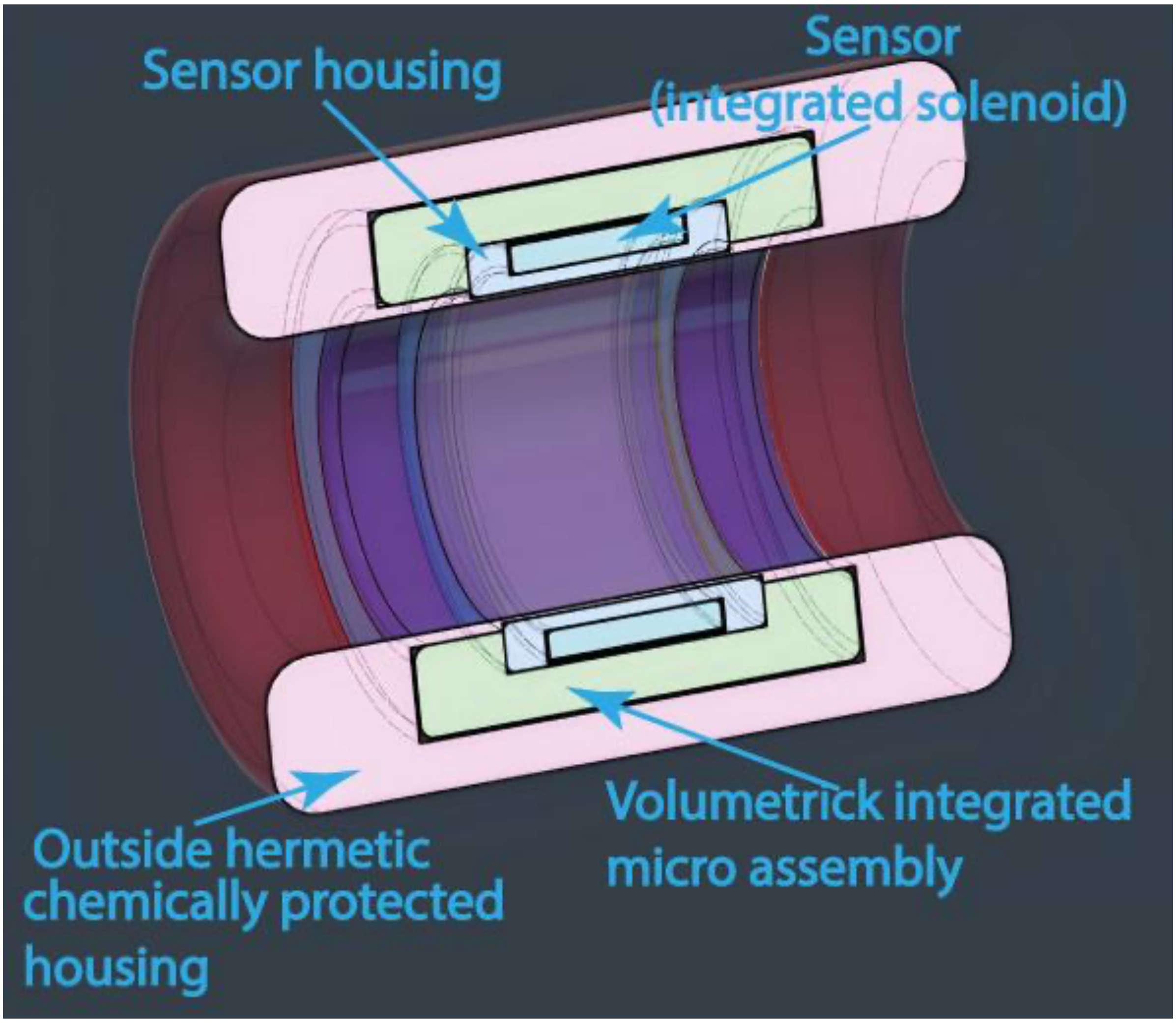
The Module's Schematic and Shape

The diagram illustrates a schematic layout of a sensor module installed on a process pipeline. This sensor device is intended for continuous monitoring of operational and technological parameters across all stages of processing, as well as within specialized industrial equipment, including local autonomous control and monitoring systems. The entire measurement and control process is based on the fundamental principles and methods of electromagnetic resonance spectroscopy and its technological equivalents.

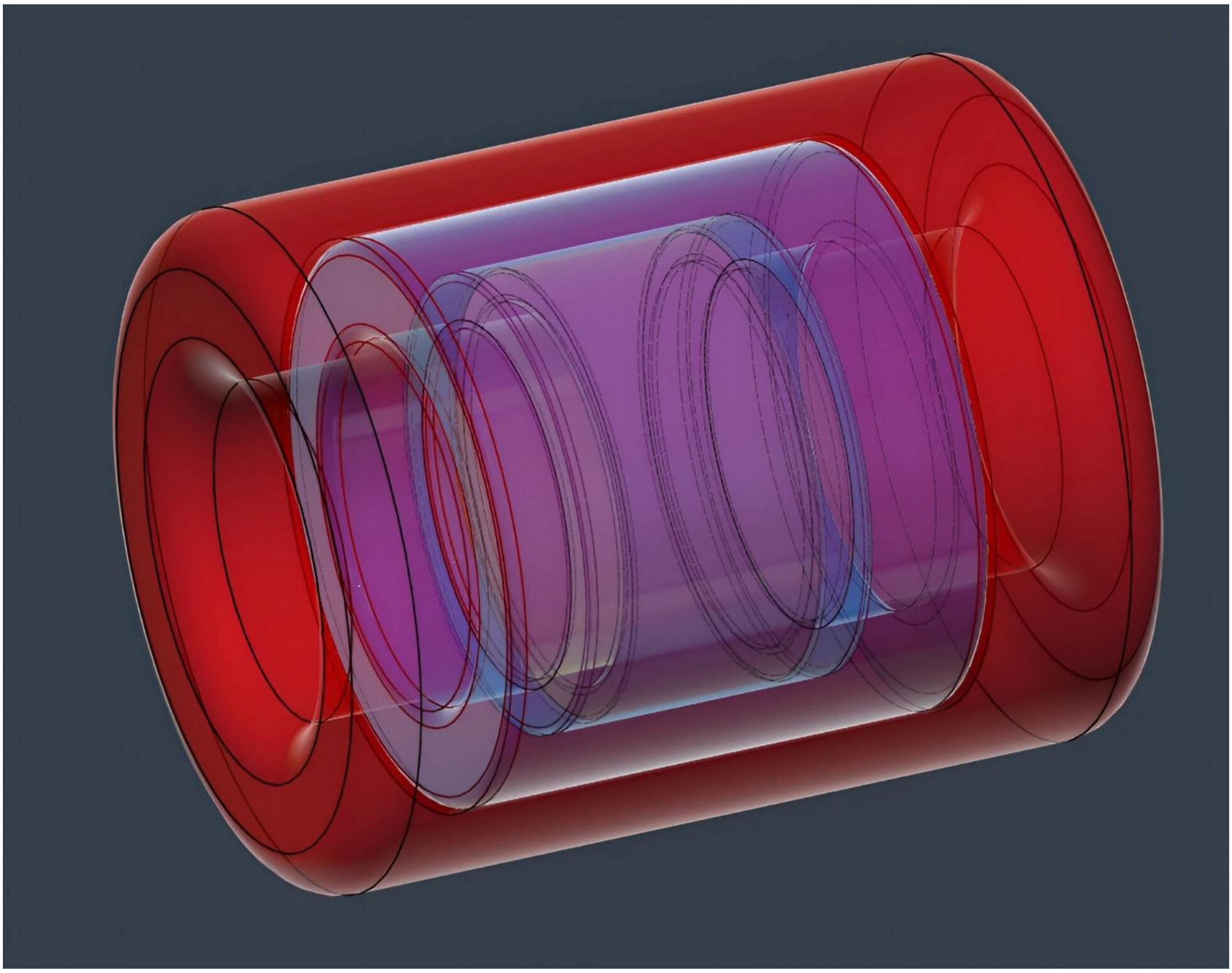
Shape of the Module

The contactless resonant-type sensor module, designed specifically for leather production, is engineered to accommodate the constraints of installation within technological equipment. Structurally, the module is shaped to align with the fundamental physical characteristics of liquid media.

To measure parameters in liquid environments, the sensor module is designed in the form of a bushing with rounded ends. This cylindrical form, in combination with toroidal inlets, ensures optimal flow dynamics and interaction with the monitored medium. The toroidal shape helps reduce turbulence and enables stable electromagnetic coupling, which is critical for accurate resonance-based sensing.



The radii of the toroidal surfaces are selected based on the viscosity of the monitored liquids in order to avoid creating hydraulic resistance and to ensure unimpeded flow through the inner bore of the bushing.



The height of micro-roughness on all internal surfaces of the bushing is minimized in order, among other reasons, to reduce mechanical resistance to the flow of the controlled fluids passing through the bushing of the sensor module.

Thus, the sensor module is adapted to the specific conditions within the process vessel.

To enable automatic monitoring of the required parameters throughout all phases of the process, appropriate mathematical models are necessary both for the process segments and for the responses of all system elements to the impedance-resonance background surrounding the sensor module.

In this article, I would like to focus on two main configurations of the sensor module;

the first configuration is designed for installation directly on the process pipeline before the inlet to the working volume of the process vessel, within the production facilities.

the second configuration is portable, designed for sampling the process solution or mixtures of process solutions from dead zones within process vessels, by extracting samples from a section of pipeline equipped with the sensor module. Both configurations of the product (the sensor module along with all necessary internal and external infrastructure) feature a streamlined design, are typically made of plastic—usually polyvinyl chloride (PVC)—and are compact and user-friendly.

The operating principle for both versions of the device is based on comparing reference signals from the resonance sensor with signals obtained from test measurements; the reference signal is acquired using a multicomponent or aqueous solution fully compliant with technological standards. The sensor of the sensor module, combined with auxiliary sensor equipment, detects the slightest deviations from the reference signal. Sensitivity thresholds are as follows:

- Metals: 0.000000005 grams;
- Radioactive isotopes: 0.000000000001 grams;
- Hardness salts and silicates: 0.000001 grams;
- Organic acids and compounds, including phenols, traces of surfactants, detergents, and mineral fertilizers: 0.0000001 grams. All concentrations are calculated per liter of water.

In its simplest form, the device (sensor module) does not selectively separate or detect individual contamination components but, due to its sensitivity, determines 50% thresholds of concentrations that are hazardous to process accuracy or to the purity and stability of the technological process, including contaminants in drinking or process water. This high precision of the autonomous industrial device (sensor module) enables continuous quality monitoring of the process and the water used, allowing for effective corrective actions before contamination or impurity concentrations reach dangerous levels.

ITM Technology

Within the sensor module system, all electronic boards and micro-modules must operate at maximum possible speed without additional energy consumption. Since the electronic sensor module is intended to function autonomously, it is most probable that a system built upon the principles of RITM technology will meet all system requirements and conditions. (RITM technology refers to dimensional selective metal etching.

Let us consider an example of such an integrated technological process. Preparation of the metal substrate.

A roll of resilient metallic material (typically steel strip, although any “springy” metal is acceptable) is taken. The surface is cleaned and activated to prepare it for subsequent coatings.

Photoresist application and exposure

A high-resolution photoresist is applied onto the strip, followed by photolithography and development to form the desired pattern.

High-velocity jet nickel electroplating

A layer of nickel (Ni) approximately 2–3 µm thick is deposited via a directed jet flow of electrolyte.

High-velocity jet copper electroplating

Using the same method, a copper (Cu) layer 25–35 µm thick is formed. The essence of the jet process is that the electrolyte continuously recirculates through nozzles, creating a directed flow. Solution parameters (Ni/Cu concentrations, temperature, pH, density, conductivity) are monitored online; due to the high renewal rate of the medium, organic brighteners are not required

Anode construction scheme

The galvanic circuit sequentially includes:

- A soluble anode,

An insoluble anode made of conductive carbon-graphite fabric. Both are connected to the positive terminal ("+") and have adjustable permeability for the electrolyte. A fine distribution system ensures uniform flow across the entire plane and, consequently, across the cathode surface of the workpiece.

Photoresist removal

Residual photoresist is stripped.

Partial base etching (first side)

Iron is etched to approximately half the thickness of the strip.

Removal of etching products

Initially by aerodynamic blowing, followed by hydrodynamic treatment (a separate innovative technology).

Polymer filling (first cycle)

The cavities are filled with a fluid monomer, which is then polymerized and subsequently thermally stabilized.

Partial base etching (second side)

An analogous etching process is performed on the opposite side.

Polymer filling (second cycle)

Re-pressing and polymerization on the second side.

Protective metal coating ("protector")

A protective layer (e.g., tin-lead or another compatible alloy with subsequent soldering) is applied to the conductive tracks.

Vacuum deposition of heat-conductive films

All heat-conductive elements are covered with a multilayer nanostructured coating of polycrystalline diamond-like (sp^3) films, which improve heat dissipation and durability.

Integration of Sensors into the Production Line

To cover all stages of the leather processing workflow, sensor modules are installed as follows:

Soaking and conditioning of hides

Several resonance sensors are mounted in the soaking tank or drum: for example, one at the bottom to monitor sediment and contaminant concentrations (dirt, salts), and another at the top to monitor overall mineralization and solution temperature. These sensors help track the effectiveness of soaking and salt removal. They can indirectly determine moisture content in hides (based on changes in the dielectric properties of the solution and the acceleration of salt concentration decline, indicating the completion of leaching). Consequently, the system can identify the optimal end time for soaking, avoiding unnecessary water and time expenditure.

Liming and hair removal

In the liming apparatus (typically a drum), sensors monitoring pH and sodium sulfide concentration maintain the solution's alkalinity at the required level. A resonance sensor tuned to ionic conductivity can serve as an indicator of lime solution concentration. It also detects compositional changes as the epidermis dissolves and hair is shed. Upon completion of hair dissolution (manifested, for example, by stabilization of the sulfide concentration sensor readings), the system issues a command to stop liming. Since direct pH measurement by resonance methods is challenging, a traditional glass-free pH meter may be integrated into the system to complement the data.

Pickling (acid treatment).

Before tanning, hides undergo acid treatment in the presence of salt. It is critically important to control the pH around ~3.0 and salt concentration to prepare the dermis for tanning agent uptake. Resonance sensors sensitive to dielectric permittivity effectively monitor salt (NaCl) concentration in the solution: changes in dielectric properties reflect the ionic strength. One or two sensors installed in the pickling drum continuously measure salinity and provide signals for dosing acid and salt, ensuring the pH profile inside the hide is optimized. This prevents "acid swelling" or, conversely, insufficient pickling.

Tanning. During chrome tanning, chromium(III) salts are introduced into the drum. Resonance sensors can monitor chromium concentration indirectly by measuring changes in electrical conductivity and dielectric permittivity. As chromium complexes bind with collagen in the hides, the concentration of free chromium in solution decreases, which the sensor detects. The control system uses this data to dose more tanning agent or stop the process once the desired binding level is reached. Similarly, during vegetable tanning (e.g., with tannins from tree bark), resonance sensors track the concentration of tanning substances in the drum. Plant tannin extracts consist of polyphenols that alter the dielectric properties of the solution as they are absorbed by the hides. Measuring resonance characteristics allows determining when the tanning solution is exhausted and should be refreshed or the process completed. Separate sensors may also measure temperature inside the drum, critical since tanning rate strongly depends on temperature; coils are equipped with temperature-sensitive elements (e.g., built-in thermistors) that influence the resonance signal.

Dyeing and Fatliquoring. These operations usually follow tanning, in the same or a separate drum. During dyeing, a resonance sensor can monitor solution transparency/absorbance (indirectly via dielectric properties) or dye concentration—especially when using metal-complex dyes that affect conductivity. While precise color control requires spectrophotometric (optical) sensors, resonance sensors help indirectly monitor dyeing completion by detecting when the solution is decolorized (dye absorbed by the hides). During fatliquoring (introduction of fat emulsions to lubricate the dermis), sensors monitor emulsion stability and distribution. Fat emulsions consist of microscopic oil droplets in water; as oil is absorbed by the leather, the dielectric permittivity of the aqueous phase changes. Resonance sensors detect these changes, allowing determination of fatliquoring completion. Temperature control during fatliquoring is also essential to ensure even oil penetration; the same sensors with temperature compensation are used.

Drying and Conditioning. After fatliquoring and washing, the leather is dried. Controlling residual moisture is crucial: under-dried leather remains too moist and prone to mold, while over-dried leather becomes brittle. For rapid moisture control, microwave (MW) methods are applicable, based on measuring reflected electromagnetic waves in the microwave range. Our system uses integrated microwave resonance sensors: for example, a pair of horn antennas mounted on the drying chamber wall operate in a differential scheme—the emitter sends an MW signal, and the receiver measures the reflection from the leather, with the amplitude linked to moisture content. This contactless, real-time moisture monitoring enables automatic regulation of drying parameters (temperature, ventilation rate, duration) and stops drying precisely when target residual moisture is reached. This prevents both under- and over-drying. Similar sensors can be applied during conditioning (rehydration of overdried leather) to ensure uniform moisture redistribution.

Finishing. The final stage involves applying coatings, oils, and colorants to the leather surface (commonly wood-resin finishes, wax mixtures, lacquers). The coating thickness and uniformity also affect quality. Resonance sensors embedded in the application line can monitor the viscosity of finishing compositions in tanks (e.g., by measuring resonance changes as the lacquer thickens or thins) and even indirectly measure the thickness of the applied layer via eddy current principles (similar to coating thickness gauges on metal substrates). Furthermore, capacitive sensors at the line exit check for full drying/polymerization of the finishing coat.

All sensors are integrated into a unified network. Each module has an address and transmits data to a controller via wired industrial networks (e.g., MODBUS, CAN) or wirelessly. Software in the controller merges data streams: by correlating readings from different sensors, the system constructs a holistic view of the process flow. For example, during tanning, data from multiple sensors (tanning agent concentration, temperature, pH) help model tanning completion degree. This digital twin of the process enables optimized control considering process dynamics and raw material properties. Importantly, the system can detect and alert on abnormal situations. If one sensor if the system detects an abnormal deviation (for example, a sudden local drop in pH in one zone, indicating an acid spill or contamination), the controller will trigger an alarm and, if necessary, halt the process. Thus, the system implements not only process control but also comprehensive safety monitoring. The use of artificial intelligence in this scheme can improve, reduce the cost of, and accelerate leather production processes.

Conclusions. Industrial hygiene standards, environmental regulations, and technological protocols in place at modern leather production facilities in developed countries require continuous quality control of all solutions, reagents, and water used at the soaking, liming, tanning, and dyeing stages. In practice, this requirement often remains unmet: there is a lack of reliable, inexpensive, and easy-to-use devices on the market that enable real-time monitoring of parameters directly inside the drum or soaking vat.

The autonomous resonance sensor module proposed in this work fills this gap. Its materials comply with sanitary and technological standards of the leather industry, and its functionality ensures precise and fast measurement of key parameters (pH, salt concentration, tanning substances, moisture, etc.). Both versions of the device (stationary in-line and portable for "dead zones") can be manufactured without rare equipment and are suitable even for small factories. Local assembly near the consumer reduces logistics costs and allows supplying modules "on wheels" without long storage times.

Further research in this area will focus on refining subtle aspects (such as precision control of specific leather properties) and on reducing costs and integrating artificial intelligence. However, it is already clear that the transition from discrete control to continuous "smart" monitoring is the key to a new level of development for the leather industry in the AI era.

References

Appendix 1

United States Patent Application 20130178721

Kind Code A1

July 11, 2013

VIVO DETERMINATION OF ACIDITY LEVELS

Abstract

A bolus for use in a ruminant animal's reticulum includes a cavity (100) configured to receive ruminal fluids present in the stomach. The cavity has walls (110) of a dielectric material and is encircled by a coil member (120), which is configured to subject the ruminal fluids to an electro-magnetic field. A Sensor element (310) measures the electromagnetic field's influence on the ruminal fluids and thus register an electromagnetic property representative of an acidity level of said fluids. A transmitter (410) transmits a wireless output signal (SD) reflecting the acidity measure.

Appendix 2

United States Patent Application 20130173180

Kind Code A1

July 4, 2013

DETERMINATION OF ATTRIBUTES OF LIQUID SUBSTANCES

Abstract

A monitoring unit (100) that determines parameters (p1, p2) of an attribute (P) of a liquid substance flowing (F) through a dielectric conduit (110) includes plural coil members (121, 122) encircling the dielectric conduit (110) that subjects a flow of the liquid substance to plural different electromagnetic fields (B(f)), and under influence thereof measuring circuitry registers corresponding impedance measures (z(f)) of the liquid substance. A processor (130) derives the parameters (p1, p2) of the attribute (P) based on the registered impedance measures (z(f)).

Appendix 3

United States Patent 8,694,091

April 8, 2014

In vivo determination of acidity levels

Abstract

A bolus for use in a ruminant animal's reticulum includes a cavity (100) configured to receive ruminal fluids present in the stomach. The cavity has walls (110) of a dielectric material and is encircled by a coil member (120), which is configured to subject the ruminal fluids to an electro-magnetic field. A Sensor element (310) measures the electromagnetic field's influence on the ruminal fluids and thus register an electromagnetic property representative of an acidity level of said fluids. A transmitter (410) transmits a wireless output signal (SD) reflecting the acidity measure.

Appendix 4

United States Patent 9,316,605

April 19, 2016

Determination of attributes of liquid substances

Abstract

A monitoring unit (100) that determines parameters (p1, p2) of an attribute (P) of a liquid substance flowing (F) through a dielectric conduit (110) includes plural coil members (121, 122) encircling the dielectric conduit (110) that subjects a flow of the liquid substance to plural different electromagnetic fields (B(f)), and under influence thereof measuring circuitry registers corresponding impedance measures (z(f)) of the liquid substance. A processor (130) derives the parameters (p1, p2) of the attribute (P) based on the registered impedance measures (z(f)).

Appendix 5

United States Patent Application 20120029845

Kind Code A1

February 2, 2012

APPARATUS AND METHOD FOR FLUID MONITORING

Abstract

According to some embodiments, an apparatus and method are provided for detecting the composition of a fluid. An alternating electromagnetic field may be applied to the fluid and distortions in the electromagnetic field are compared with predetermined, expected distortion «signatures» for particular components at particular concentrations. The presence and concentration of the components in the fluid may be detected by detecting these distortion signatures.