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A REVIEW ON SMART SENSORS USED IN CHEMICAL INDUSTRY 4.0

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Abstract— Sensors have a huge role in various industrial sectors in the development of smart and automated operations. Due to technological growth, different types of sensors are available in the industrial markets, which are mass-produced and reasonably priced. For instance, the temperature sensor, position sensor, pressure sensor, flow sensor, etc are increasingly used in the chemical industry 4.0. The main purpose of this work is to conduct a detailed review for analyzing the different types of sensors used in chemical plants. Also, it intends to investigate the issues, challenges, applications, and demands of the sensors used in smart industries. Typically, the primary advantages of using smart sensors are increased productivity gain, environment security, adaptability, high lifespan, etc. Moreover, this review investigates the major impacts of using smart sensor technology for industrial development and growth. According to the analysis, it is observed that smart sensors are now an essential part of integrated systems because they have an inbuilt module that supports communication and information exchange operations. For evaluation, the performance and efficiency of the smart sensor technology are validated by using various parameters.
Index Terms— Industrial Internet of Things (IIoT) 4.0, Smart Sensor Technology, Chemical Industry, Automation, and Process Management.

INTRODUCTION

In recent times, numerous industries use the different types of sensors for regular and commercial purposes [1, 2]. Due to their remarkable capabilities, the utilization of sensor systems is extensively grown in the industrial sectors. Specifically, the sensors [3] are mainly used to enable communication across various machines, systems, and devices. Moreover, the sensors [4] have excellent onboard processing capabilities, they can evaluate the atmospheric conditions and adjust operations as necessary. The world's demand is always rising, placing pressure on the global production sector, and as a result, businesses must continuously boost their quality and productivity [5]. The majority of businesses worldwide are using novel machineries to regulate performance data, estimate manufacturing processes, and transform and regulate the specifications of improved production, to create new business values, to remain sustainable in the world and to accomplish all aforementioned requirements. Real-time control and information are achieved by integrating the new machineries that has led to Industry 4.0's [6, 7] (smart technologies) core into the production processes. These networks and technologies are used to control the company's production line. Industry 4.0 [8] is built on intelligent sensors, which helps to enhance the company's total business performance and productivity. Moreover, smart sensors [9, 10] are now an essential part of integrated systems, because they have inbuilt modules that support communication and information exchange operations. Fig 1 shows the main building blocks of smart sensor technology.

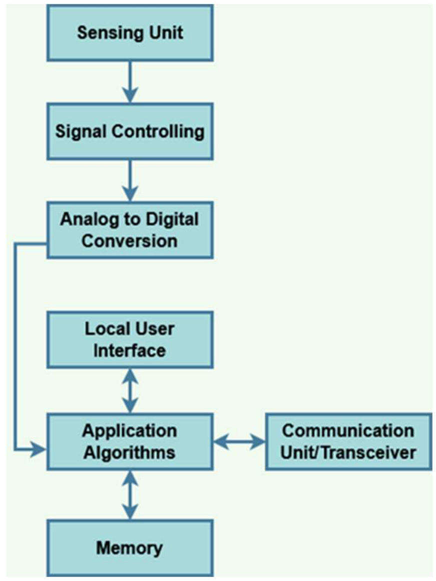

Fig 1. Main building blocks of smart sensor technology

Due to the addition of smart sensors in Industry 4.0 [11, 12], the organization can gain the following benefits:

- High productivity gain
- Business adaptability
- Fast response to marketing change
- Better system design and business adaptability
- A maximized lifetime of the product and minimal energy utilization
- Environment security

The goal of a new approach to managing manufacturing processes is to increase efficiency and effectiveness, utilization of the data already available, and apply a combination of technologies [13, 14] that can help the system or production process. An interconnected and intelligent network that advances intelligent production is required for Industry 4.0. For efficient decision-making, sensors [15, 16] can collect and analyze, and self-optimization is conceivable for automation in manufacturing processes. All customized product solutions and assembly processes can be optimized through factory automation. Asset management technologies [17] are anticipated to be adopted by the sector in the next years. For efficient supply lines, the supply chain industry mainly depends on asset monitoring technological solutions, which leads to strong demand on the market globally. Then, this technology would be heavily utilized for process management across numerous industries. When automated industrial processes are used along Industrial Internet of Things (IIoT), sensors [18] will have significant growth potential. The major objectives of this article are as follows:

- To present a comprehensive review for analyzing the diverse kinds of sensors used for chemical industry 4.0 systems.

- To investigate the major impacts of using smart sensor technology for industrial development and growth.
- To examine the roles, capabilities, and applications of smart sensors for improving the automation and sustainability of smart factories.
- To validate the performance and efficacy of the sensor technologies by using various evaluation parameters.

The remainder of this paper is structuralized into the following sections: Section II reviews the conventional works linked to the diverse kinds of smart sensors in the IIoT 4.0 systems. Also, the detailed investigation of the research methodology is presented with a clear explanation in Section III. Lastly, the complete paper is abridged with the findings, and upcoming opportunities in Section IV.

Related Works

This segment inspects some of the conventional approaches associated with the different types of sensors used in IIoT 4.0 systems. Moreover, it examines the benefits and challenges of the existing works according to the working operations and features.

Schutze, et al [19] presented a comprehensive analysis of the sensor technology for efficient industrial automation and control. The purpose of this work was to enable self-monitoring and self-configuration in the industrial sectors with the use of smart sensors. Most of the industrial sector's object to increasing product quality, flexibility, and productivity by using smart sensor technology. Moreover, this work addressed the importance of using sensors, instrumentation, and measurement units for the development of industries. Eifert, et al [20] investigated the current and future requirements of IIoT 4.0, where the new Process of Analytical Technologies (PAT) was discussed for increasing the effectiveness of products. The conceptual framework of smart sensors used in the IIoT 4.0 systems is shown in Fig 2, where the physical twin was fed by the chemical information elements.

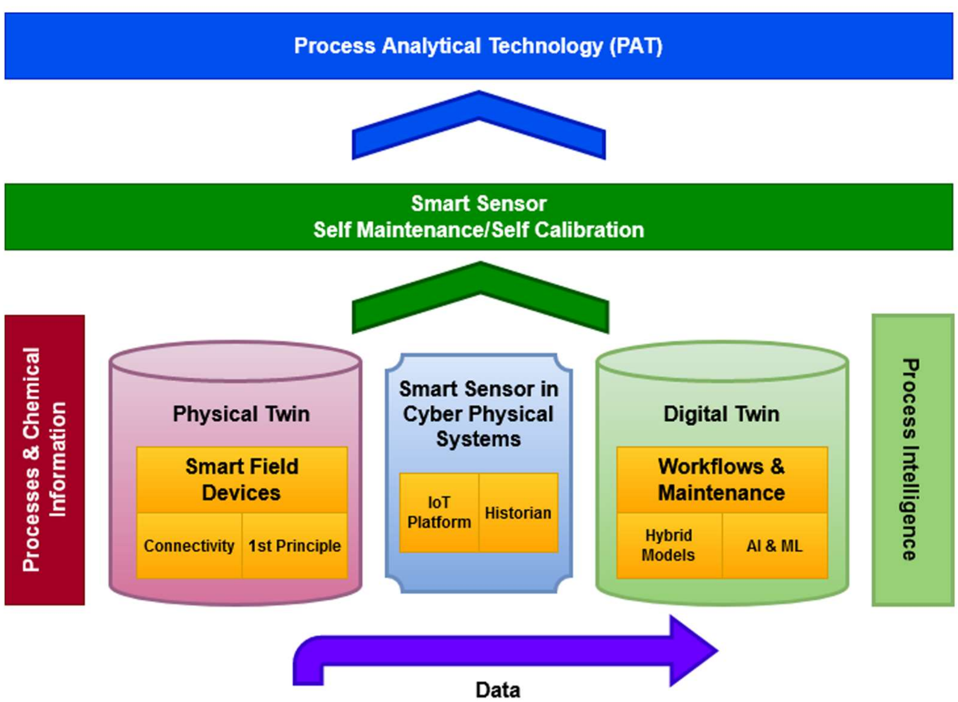

Fig 2. Conceptual framework of future smart sensors

Mantravadi, et al [21] employed a Quality Function Deployment (QFD) method for determining the designing requirements of Industry 4.0 systems. Here, both the high-level and low-level domain requirements were validated for ensuring the security of smart factories. Gupta, et al [22] investigated the major impacts of using smart sensors in IIoT systems. Typically, smart sensors were mainly used in various industrial application domains for improving the production and service quality Sehrawat, et al [23] presented a comprehensive investigation of the varied kinds of IoT sensors used in these industries. These sensors were mainly for knowing the ecological and operating settings of the smart environment.

Research Methodology

Typically, the chemical and physical properties are changed in the process industry [24]. Monitoring the process is one of the most significant operations in the chemical industries [25], where the chemical reactions are controlled according to the specific information of the closed loop. In this framework, the smart sensors [26, 27] play an essential role, because it supports improving the product life cycle and robustness. In general, the sensors are device chiefly to sense the input as a property/ quantity and then responds to that signal. The arrangement of sensors is based on the type of sensed object, such as temperature, speed, velocity, heat, closeness, smoke, chemical, liquor, etc [28]. The output of a sensor can be in terms of voltage, current, inductance, resistivity, speed, or some other electrical property that changes with time. Based on the measurement, fields of usage, transformation principle, energy domain of the measurement, and criteria like chemical contemplations, the sensors are categorized as different groups. Sensors enhance the market broadly and make up for the rising labor shortage. These advancements can easily facilitate in the investigation of those instruments used in the compressed air applications in the manufacturing industries. The fluctuations are easily identified by the smart sensors and they can generate troubleshooting alarms to repair the precise failure in these devices. Intelligent sensors [29, 30] can be used for a variety of purposes.

To ensure that the Instruments receive adequate heat, they are installed totally in the combustion chambers like ovens, hobs, etc. he original capabilities of sensors used in industry 4.0 are graphically represented in Fig 3, which encompasses the core functionalities of Maintenance, Automation, Monitoring, and Process Automation.

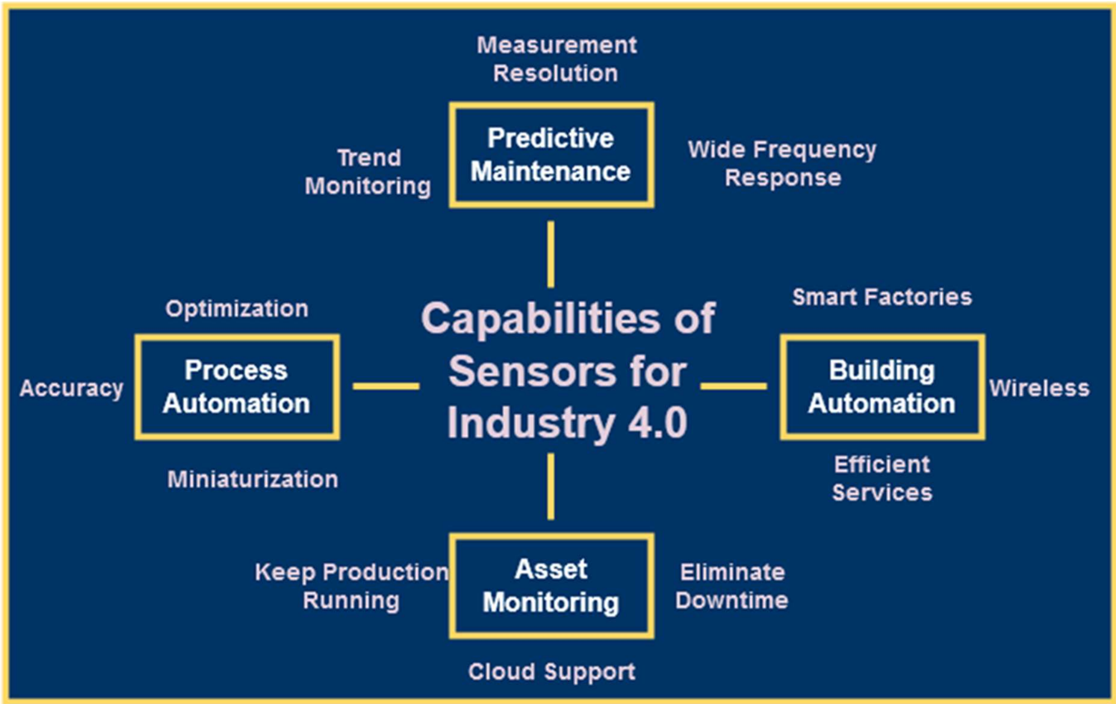

Fig 3. Capabilities of Sensors in Industry 4.0

Various Sensors used in the Smart Industries

The original contribution of this paper is to present a detailed review for studying the different types of sensors [31] used in the chemical industry 4.0. Typically, sensors are the mainstay of the products and services, and are able to keep an eye on the key process variables that have an impact on output, economy, and safety. To benefit from the IIoT [32], the device networks must coordinate and exchange the massive amounts of data that the multiple system sensors have collected. The different types of materials used to design the sensors are illustrated in Fig 4, and its associated parameters are shown in Fig 5.

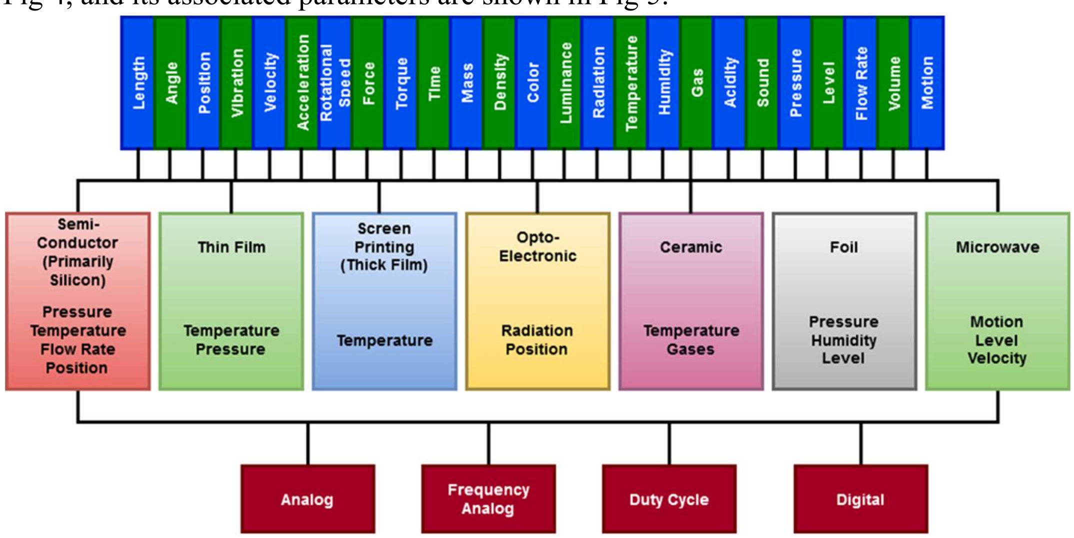

Fig 4. Materials of sensor

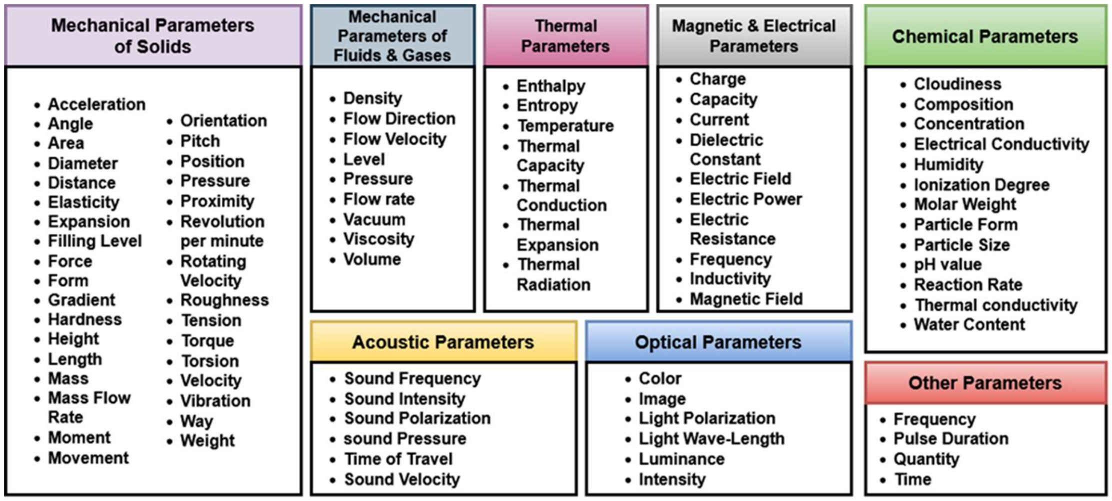

Fig 5. Parameters of sensor

- Proximity sensors - With a proximity sensor, any adjacent object may be easily located without making direct physical touch. It locates the existence of an object by observing for fluctuations in the signal by producing electromagnetic radiation [33, 34], such as infrared. Numerous types of proximity sensors, including inductive, reactive, infrared, optical, electromagnetic, and many others, are available for various purposes. This specific sort of sensor is frequently utilized in applications that demand efficiency and security. This sort of sensor has several applications, including object detection, item counting, rotation measurements, item positioning, substance detection, motion direction quantification, self - parking, and others. The best uses for proximity sensors span a wide range of sectors.
- Position sensors - By observing their mobility, the position sensor can determine whether there are people or other objects in a specific space [35]. The owner may track the appliances from anywhere by using it for home security. They were able to see if the area was open or closed, and it could even find intruders while they weren't there [19]. It can be used in agriculture to locate animals, in health care to track the locations of patients, nurses, and doctors in a hospital.
- Occupancy sensors - The occupancy sensor, also known as the presence sensor, determines whether there are people or items present in a specific space [36]. Through a number of characteristics, including temperature, humidity, light, and air, it can be utilized for remote monitoring.
- Motion sensors - An instrument to detect all kinds of movement in the atmosphere is a motion detector. Motion sensors [37, 38] can be used in an application for monitoring residences while the owner is away, and whenever some movement is watched those pictures or videos are sent to the server.
- Velocity sensors - It is a sensor that figures [39] out how quickly constant position measurements and position values change at predetermined durations. An angular or linear velocity sensor is possible, which measures how fast an object is moving in a straight line, whereas an angular velocity sensor [40] determines, how quickly a device is rotating.
- Temperature sensors – The temperature sensors [41] are useful for identifying physical changes in the body based on heat energy. Also, it is used to monitor the ambient

conditions of the immediate area, in which the acquired data is transmitted through wireless with the help of smart devices.

- Pressure sensors - Sensing the total force, pressure sensors translate into signals. Then, these sensors are increasingly used to monitor health [42].
- Chemical sensors - Chemical sensors [43] are analytical tools used to determine the environment's chemical composition. A wireless chemical sensor network can be used to monitor the environment's chemical emissions to determine the quality of the air. Chemical sensors [44] are devices that detect any chemical reaction, molecule, or mixture of substances. These sensors can be employed to evaluate the state of the environment, the health of structures, agricultural conditions, and more.
- Humidity sensors - A humidity sensor [45] determines the environment's relative humidity by measuring the temperature and moisture content of the air.
- Water quality sensors - Ion monitoring utilizes [46] this sensor for groundwater recharge, where, the sensors monitor water quality with proper readings. A low-cost device that could be helpful to monitor the water quality in an Internet of Things (IoT) environment by detecting the temperature, electricity, sedimentation, PH, and chemical oxygen demand of the water.
- Infrared sensors - In order to sense various characteristics of specific objects, infrared sensors may emit or detect infrared radiations. These sensors [47] can be used for home automation in order to monitor and manage household devices, such as for switching the lights on and off. Additionally, it is applied to smart parking, garbage collection systems, and smart security system.
- Gyroscope sensors - Gyroscope sensors [48] measure angular velocity to identify any tilt or angular movement in the item. It is widely used in 3D mouse games, athletic training, robots, factory equipment, and numerous other applications.
- Optical sensors - In order to detect electromagnetic energy like light, optical sensors [49, 50] are essential. These are usually utilized in IoT applications, also in digital cameras, as they are inactive to all types of electrical inputs. IoT applications involving energy, healthcare, the environment, chemical plants, process industries, aviation, and other fields benefit from the use of optical sensors.

Table 1 validates major types of sensors used in smart industries for improving the system automation and operations.

Table 1. Diverse Sensors of smart industries

Types of Sensors	Purpose
Light sensors	It is also termed as the photoelectric device that is used to convert the photons into electrons. These sensors are extensively having a function in various industrial sectors. But, the operations of photo resistors, transistors, and diodes can operate differently with a unique application.
Color sensors	It is a type of photoelectric sensor mainly used to emit the light from the transmitter. Also, it is used to detect the object at the receiver side. It can be widely used in various applications

	like medical diagnosing systems, image processing systems, health fitness, color identification, and etc.
Flow sensors	These are the electro mechanical instruments mainly used to sense the properties of fluids. Also, it provides an efficient method to estimate the gas concentration and environmental information.
Humidity sensors	These types of sensors are mainly used to estimate the amount of water in the environment, which uses the input stimulus for converting the measurements into the signals. It is widely deployed in the manufacturing industries, automobile sectors, meteorology, and etc.
Proximity sensors	It efficiently detects the existence of things and components without physical contact.
Temperature sensors	It accurately detects the thermal parameters from atmosphere, and changes the input data into an electrical data according to the measured input. For instance, thermometers are one of the most commonly used temperature sensors to compute the degree of hotness.
Pressure sensors	Typically, it is used to measure the pressure of gases or liquids. Based on its design, application, performance and cost, it can be significantly differed from other sensors.
Force sensors	The force sensors are treated as the devices transforms the applied mechanical forces like compressive and tensile. Then, it produced the output as the digital signals. These sensors are also widely used in different applications like consumer products, computer devices, automotive, sports, and etc.
Gas sensors	These types of sensors are very portable in nature, which detects the existence and properties of gases according to output signal of controller. Moreover, it detects the harmful gasses by monitoring the gas and environmental information.
Flaw sensors	It is mainly used in the manufacturing industries for identifying the problems in the materials.

Sensors used in the Chemical Industries

The central objective of "smart factories" is to construct production facilities successfully and in a networked fashion by using intelligent production systems and appropriate engineering methodologies. It is a system of engineering that relies on connection, cooperation, and execution. Smart factories are adaptive due to the interconnected equipment that enable information sharing [51, 52], situation recognition and assessment, and integration of the physical and digital worlds. Smart sensors have gained an increased attention recently among other technological advancements [53], because of their significance and diverse applications. Everyday sensors are also becoming smarter thanks to the combination of computation and the internet of things, due to complex calculations of the data. Smart sensors [54, 55] have not only become more powerful but also remarkably compact and flexible, transforming heavy machinery into high-tech intelligence.

Smart sensors have advanced into complete devices with self-calibration skills thanks to their signal-conditioning, interior algorithms, and interfaces. The key features and characteristics of these sensors used in the industry 4.0 are represented in Fig 6.

Calibration Capability - Calibration capability [56, 57] is the phrase used to describe a sensor's capacity to ascertain its typical function. Self-calibration is often simple, and many calibration techniques are used in the smart industries with various sensor technologies.

Fault Diagnosis Capability - By examining internal signals [58-60] for signs of errors, intelligent sensors do self-diagnosis. Some sensors may have trouble differentiating between typical measurement variations and sensor flaws. To get around this problem, numerous measured values are recorded around a setup point, and the measured quantity's minimum and maximum values are calculated. Uncertainty techniques are applied to quantify the effect of sensor malfunction on the measured quantity. This permits the use of a sensor even after a problem has occurred.

Micro-Sensors – Micro Electro-Mechanical System (MEMS) devices are defined as the component of micro-sensors, which incorporates two and some times more than two dimensional micro assemblies. Generally, these tiny transducers convert mechanical impulses into electrical signals.

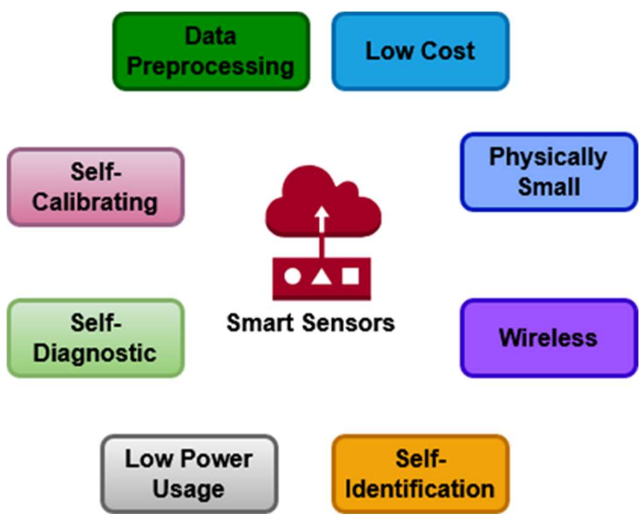

Fig 6. Features and characteristics of smart sensors used in Industry 4.0

Table 2 to Table 4 analyzes the characteristics, applications, benefits and limitations of the temperature sensor, pressure sensor, and flow sensor, which are increasingly used in the chemical industry 4.0 for process automation and proper functioning.

Table 2. Analysis of temperature sensor based on their characteristics, applications, benefits and limitations

Type of Sensor	*Features*	*Type of Material used*	*Applications*	*Pros & cons*

Thermistor	These are heat sensitive resistors, and they vary actually when the temperature varies. The ideal operating temperature range is from 50℃ to 250℃.	The things protected with glass, such as manganese, nickel, or cobalt oxides	It is highly used in the to determine coolant and incoming temperature	Fast thermal responses, Less accuracy due to lead resistance. Finite working range
Resistance meter (RTD)	A constant relationship with temperature; resistance fluctuates as temperature changes. The ideal operating range is 50℃ to 500℃ using a thin film and, 200℃ to 850℃ with a wide film.	Conducting metals like metal, copper, or nickel.	The applications are HVAC, space, ductwork, and coolant temperature sensors; overcurrent protection for machines; and gas in automotive.	Costly; vulnerable to lead wire resistance; delayed thermal response
Thermocouple	Temperature fluctuations result in a voltage that is temperature sensitive, which is then converted into a temperature reading. Operating range is to measure temperatures as low as 250℃ and as high as 3000℃.	Junctions of combination various metal alloys, such as copper and constantan.	Since it is affordable, tough, and reliable, hence it is most frequently employed.	Extensive temperature range, precise temperature measurement.

Table 3. Analysis of pressure sensor based on their characteristics, applications, benefits and limitations

Type of Sensor	***Features***	***Type of Material used***	***Applications***	***Pros & cons***
Resonant	It uses a diaphragm attached to a magnetic coil that vibrates when exposed to a magnetic field carrying an electric current, which is based on the vibrating wire idea.	It uses the metal created resistors like silicon and quartz.	It is highly employed in industrial vacuum and gauge measurements.	Air pressure and explosion pressure.
Capacitive	When pressure is applied to the elastic elements, there is a change in the	Copper and Indium tin oxide.	Most suitable for stream applications.	Massive overloads; Applications are restricted by

	capacitance which generates an oscillator frequency.			chemical restrictions and attaching and closing requirements.
Optical	To measure distinctions in pressure using optical cable, use interpolation. can be created with micro - electromechanical systems or small machineries.	Use a Circularly polarized interferometer.	It is used in radiographic devices.	Good efficacy, compact size, and extended life period; not influenced by any electro-magnetic interference, clinically acceptable for installation. Expensive; prone to physical damage and environmental impacts.
Piezoelectric	It uses the dielectric crystals, such as silicon, to cause a charge directly proportional to the pressure.	Piezo - electric materials like tanzanite, barite titanium, sillimanite, and quartz.	It is to detect pressure in storms, explosives, and motor burning. It is also applied in some elective surgeries, including the monitoring of vascular pulse.	Monitors dynamic pressures that change quickly. Solid state pressure cannot be measured due to its dynamic character; requires high impedance circuit; subject to noise.

Table 4. Analysis of flow sensor based on their characteristics, applications, benefits and limitations

Type of Sensor	***Features***	***Type of Material used***	***Applications***	***Pros & cons***
Mass flow	(1) presenting heat energy, assessing variation in temperature (2) keeping a steady temperature and assessing the power required for that (3) presenting charge to a resistor wire and	It deals with hostile gases, special alloys.	Extensively applied in automotive industrial sectors.	Bidirectional flow monitoring; wide range of detectable fluids, especially high viscosity liquids; control and data of liquid flow with high accuracy. High accuracy direct liquid flow

	extent of current required to sustain temperature.			measurement; a large variety of detectable fluids, such as very viscous liquids; reversible flow measurement
Velocity flow	Sensors measure the fluid's flow rate as it passes through the device to measure the flow rate. It encompasses properties of mechanical, ultrasonic, and electromagnetic.	Wall of stainless-steel pipes, platinum, tantalum, iridium, and titanium.	It is widely utilized in the chemicals and petrochemical industries.	Does not work with quasi fluids; enough conductivity is required; not appropriate for vacuum conditions.
Positive displacement	Determines the volume of the fluid right when it passes from the instrument.	Stainless Steel	It is used for measuring mechanical fluids, lubricants, fuel, and gas and water sensors that are installed in homes.	Provide mechanical or electrical interface; operate across a wide range of fluids; Due to the moving parts, installation and maintenance are incredibly costly.

Table 5. Analysis of force sensor based on their characteristics, applications, benefits and limitations

Type of Sensor	***Features***	***Type of Material used***	***Applications***	***Pros & cons***
Load cells	Transforms the applied force into a signal that can be used to additional parameters, like mechanical stresses. Include ferromagnetic, capacitive, inductive, and mechanical crystal load cells among others.	Materials like magnetic, working electrode, metals resistance etc.	Extensively used in transportation	Force affects performance; temperature network is necessary; Large forces can damage the load cells. Lightweight and compressed are precise, affordable, responsive.

Strain Gauges	Sensors that adjust their resistance in response to the applied pressure.	A foil that has an insulating substrate.	Truck scales to bolt tensioning equipment are all often utilized in load measuring applications.	Low cost; good resolution; tiny dimensions; detects static and dynamic stress. Minimal accuracy; and requires calibration.
Force Sensing Resistors (FSR)	Utilize a form of piezo - resistive technology where a semi-conductor material, like ink, is placed among two surfaces that are separated by a separator.	PCB, conducting padding, and mechanical and electronic components.	It is highly used in foot pronation control systems, etc.	Simplicity, low energy consumption, lightweight available in many shapes and sizes. Measurements taken repeatedly have poor precision and reproducibility.

Conclusion

This paper is basically an analysis of diverse types of sensors used in chemical industry 4.0. Also, it investigates the issues, challenges, applications, and benefits of the sensors of the chemical plants. According to this analysis, it is observed that the smart sensors are continually being developed and adopted in all sectors of society as a result of the development of novel machineries. Around the world, many advanced businesses are adopting Industry 4.0. Without the intelligent sensors, it would be impossible to automate all operations from raw materials to final products. Smart sensor integration with the manufacturing procedures connects the business and lessens the complexity of those procedures and errors. It enables users to access information that can enhance the efficiency and effectiveness of the equipment and leads to decrease in the average time of breakdowns. Implementing smart sensors in the manufacturing process has many benefits, some of which include: defect detection, reduction in downtime and maintenance planning, improved supply chain management, increased productivity, quick switching to the production of other products, improved worker safety and health, high production quality, reduction and planning of electricity consumption, etc.

In future, this work can be enhanced by implementing an advanced and intelligent sensor technology for improving the business development of chemical industry 4.0.

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