Waste Hydrogen Pipelines Monitoring in Modern Power Plant

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ABSTRACT

Many production processes in chemical industry generates hydrogen as a by-product. Part of this is reused in the other production process, however significant amount that is wasted can be used for energy production in stationary application. The goal of the project was development of the technology for safe exploitation of by-product hydrogen in chosen chemical plant. During the pilot project a small power plant with electrical capacity of 1 MW was designed and constructed. Two energetic technologies were applied. First use hydrogen and hydrocarbons as a fuel for combustion generators (leading technology), and the second one use purified hydrogen for fuel cells (complementary technology). A big attention was put on safety aspects and structural health monitoring of the most critical elements. An innovative technology based on distributed optical fiber based sensors for hydrogen pipeline integrity and leakage detection was applied. A temperature distribution along each of four supply gas pipelines (one with pure hydrogen to the fuel cell and three others with waste hydrogen to power generators) is permanently monitored.

KEYWORDS: *waste hydrogen, SHM, distributed optical fiber sensor, power plant*

INTRODUCTION

The importance of hydrogen as an energy carrier is growing. A term of *hydrogen economy* [1] is even used to highlight the growing, and in the future, the dominant role of this fuel, in opposition to commonly used hydrocarbons. Hydrogen production in 2004 was about 50 million tons [2], which is equivalent to approximately 170 million tons of oil. Moreover every year there is an increase of production at the level of about 10%. The present trends show that in the future an innovative power engineering will be based on local energy sources (also small ones), which will be stored in the form of hydrogen [3].

Hydrogen is also a by-product (also called waste hydrogen) of many industrial processes like production of chlorine and caustic soda. Some of this hydrogen is reused in the production process, however significant amount that is wasted can be used as a fuel for transportation equipment and in stationary applications. In Europe about 23bn m^3 per year of by-product hydrogen is produced every year (mainly in chemical plants) and between 2 and 10 billion m^3 is wasted. This amount of hydrogen would be enough to power up more than 1 million vehicles with hydrogen power cells or to produce heat and electrical power for industrial purposes [4].

Hydrogen, which is being valuable fuel, shown at the same time many features that affect the safety of its use. This is a consequence of such facts as:

- colorless, odorless and tasteless,
- highly reactive with oxygen and other oxidizing agents; the ratio of hydrogen in the air, at which ignition occurs is in the wide range from 4% to 75.0%,
- highly explosive gas; explosion in the air can occur when the hydrogen content in the range of 18.3% to 59% by volume [5, 6],
- a low ignition energy (0.02 mJ); it means that the mixture of hydrogen can be ignited in air by using an energy of 1/10 comparing to the fuel ignition.

The project “The use of waste hydrogen for energy purposes” is realized in Azoty Group company in Kędzierzyn-Koźle, which is one of their largest chemical plant in Poland. The pilot project was started in 2013. The main goal was to develop a technology for exploitation of by-product hydrogen for energy production. Two methods using by-hydrogen as a fuel were implemented (Figure 1): combustion in a specially designed generators and fuel cells (after purification). A special emphasis was placed on safety issues and structural health monitoring of the most critical elements, including fuel pipelines [5].

a) b)

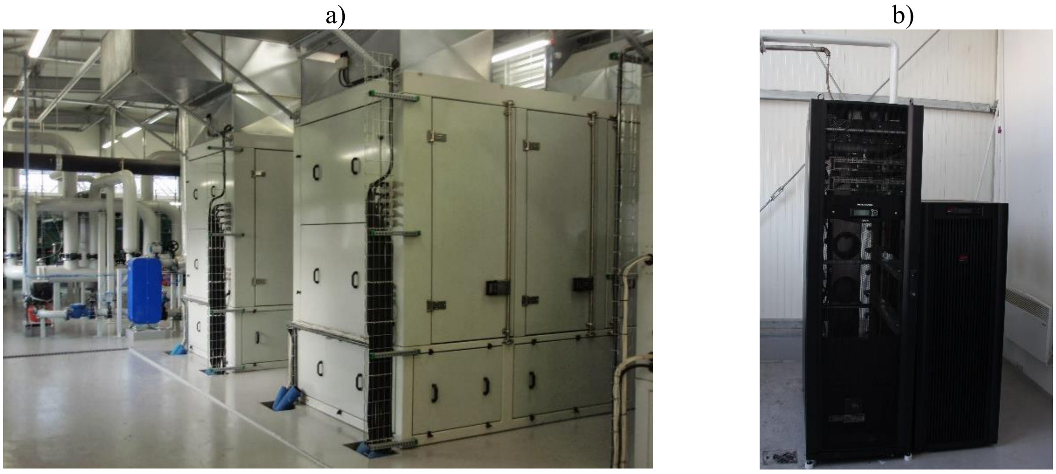


Figure 1: Main technology hall of the hydrogen power plant: power generators (a) and fuel cells (b)

1 STRUCTURAL MONITORING OF HAZARDOUS PIPELINES – LEAKAGE DETECTION

Safety of pipelines designed for the transport of dangerous substances (flammable and/or explosive) is an important problem for their owners and operators. This concerns both: gas pipelines, pipelines for crude oil transportation, as well as the pipelines in chemical industry (e.g., transport of chlorine, ammonia or hydrogen), and power plants (e.g., transport of water vapor under high pressure).
Often, even a small failure in the form of leakage causes measurable effects on the environment (possible contamination), as well as economical for the owner of the pipeline (temporary shutdown, loss of transmitted raw materials, compensation for environmental pollution, the possibility of explosion and damage of the infrastructure, etc.), not mentioning a direct threat to people. Therefore it can be concluded that the assessment of technical performance of pipelines is difficult and responsible task, particularly in the case of pipelines for the transport of hydrogen.

The best method of protection is to avoid explosive situations which favor the possibility of explosion and minimize the risk. General guidelines for the explosion prevention are set by industry standards [6], which define such steps to be taken as: hazard identification, risk assessment, evaluation of the possible effects of an explosion, the elimination or minimization of the risk, or the development and follow safety procedures. Minimization or total elimination of the risk is based on minimizing the possibility of occurring an explosive substance, an oxidant and an effective ignition source at the same time [6]. Therefore, the use of structural health monitoring systems for fuel pipelines, including hydrogen ones, minimizes the risk of explosion by eliminating one of the components of fuel. Moreover, this method can assist other preventive actions, such as ventilation or inerting, whose task is to control the composition of the atmosphere [7].

A very important difficulty in monitoring pipelines is their significant length. This causes that the application of standard measurement methods (e.g., strain gauges, thermocouples, acoustic emission, etc.) is very limited. The typical transducers are used mainly for point measurements and designing of a network covering the whole object is economically ineffective. Therefore, the most optimal solution is to use measurement systems based on fiber optic technology, with particular regard to distributed systems.

In the literature related to structural health monitoring of pipes it is possible to find many papers describing optical fiber based SHM systems. They are mainly used for the leakage detection (e.g., [8]), strain state monitoring (e.g., [9, 10]), or assessment of degradation or corrosion processes (e.g., [11, 12]). Basic idea behind the leakage detection is the assumption that leak changes local temperature distribution around the pipe [13]. Thus, depending on the type of the pipeline and its intended use, as well as the ambient conditions, following phenomena can be present:

- a local increase in temperature (usually in the case of liquid leaks or gas with a negative Joule-Thompson coefficient),
- a local drop in temperature (usually in the case of leaks from gas pipelines: positive Joule-Thompson coefficient and decompression).

2 PRELIMINARY ASSUMPTIONS FOR SHM SYSTEM

Designing of an effective SHM system for hydrogen pipelines was realized on the basis of approach represented by D. Inaudi and B. Glisic [13, 14]. In the first stage (Identify structures needing monitoring) an analysis of the object was done. The whole power plant project was supposed to be a demonstrator of innovative power engineering technologies, so the SHM system should also meet this criterion. It applies new solutions for the use of waste hydrogen, which were not applied in Poland for energy purposes before. The gained experience will be used in the future in other industrial plants where suitable fuel is available. The analysis showed that because of the operation of the power plant (the continuity of fuel supply) and the safety of employees and the installation (power station is located directly in the chemical plant), it is critical to ensure the reliability and full operation of the pipelines which feed power generators and fuel cells. Any failure in this area could have serious consequences in the functioning of the chemical plant.

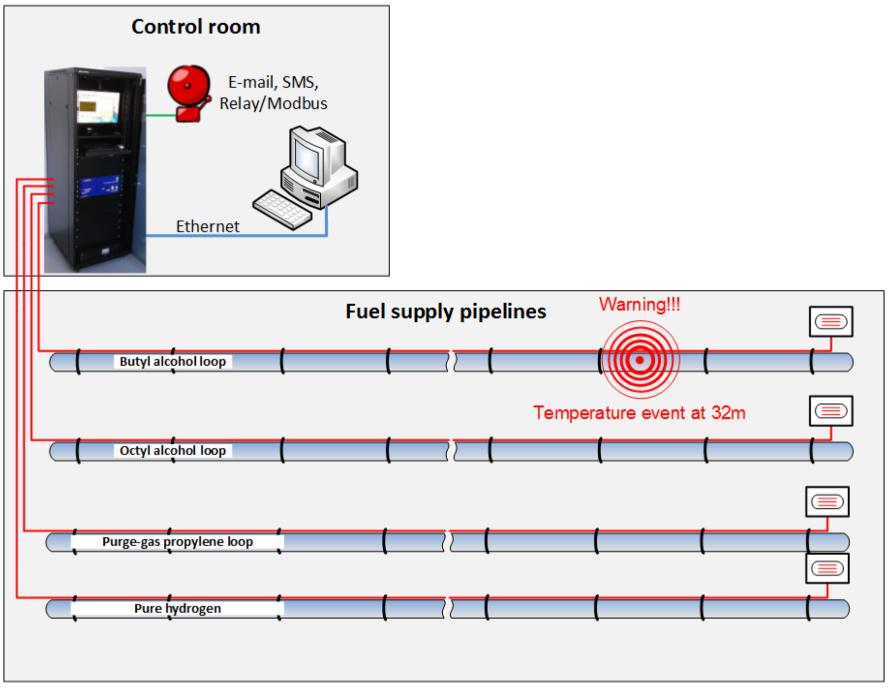


Figure 2: Scheme of pipeline monitoring system

In the next step a risk analysis has been investigated and the main hazards that can lead to fuel leakage were identified. The most critical are: hydrogen embrittlement (leading to the degradation of the mechanical properties of the carbon steel pipelines), external impacts (rack pipeline over internal road) and foundation settlements. It was pointed out that the direct consequence of the waste hydrogen fuel leakage will be change of the local temperature conditions. Its temperature is in a range of 35÷45 ^{0}C and even a small leak should be properly detected and located. For this reason and due to safety aspects (i.e., protection against spark ignition) it was decided to implement the system based on distributed optical fiber sensor technology.

The project of sensors arrangement assumed that they will be installed along the entire length of the fuel pipelines that have arisen during the power plant investment process. Due to the physico-chemical properties of fuel (mainly gas fraction), it was proposed to put the sensor on the top surface of the pipeline. Such positioning of the sensor head allow detection of a potential leak in a much shorter time. The idea of the measurement system is shown in Figure 2.

3 CONFIGURATION OF THE PIPELINE LEAKAGE MONITORING SYSTEM

3.1 Distributed optical fiber based monitoring system

In the distributed OF systems a light scattering phenomena inside the optical fiber is used, in particular the phenomenon of so called Brillouin and Raman scattering. The sensor head in these systems is the total length of the optical fiber connected to the measuring system. This means that the measured quantity is processed continuously along the entire length of the optical fiber (multi or single mode). The length of measuring arm of these sensors may in special applications (including EDFA amplifier) reach even 150 km. Measurement resolution (called: spatial resolution), which is the minimum length of fiber, for which the system is able to distinguish measurands, depends on the reading unit quality. The spatial resolution is typically within the range from 1 cm to several meters.

In the project an innovative technology based on Raman principle for hydrogen pipeline integrity and leakage detection was applied. The spontaneous Raman scattering phenomenon refers on the scattering of photons on the oscillating glass fiber molecules. This oscillation depends on temperature changes. The frequency of the new wavelength is shifted by the characteristic oscillation frequency for the glass molecules. Due to scattering in the spectrum two additional bands are visible (see: Figure 3). They are called: Stokes and anti-Stokes waves [13]. The intensity of anti-Stokes wavelength strongly depends on temperature variations. To determine the temperature inside the sensor, a ratio of the Stokes and anti-Stokes waves is calculated.

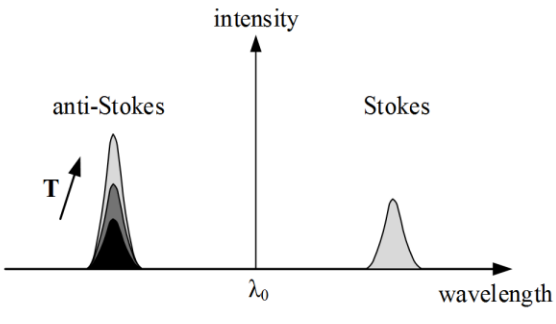


Figure 3: The Raman backscattering principle (based on: [13])

3.2 Installation of optical fiber sensors on the hydrogen pipelines

The monitoring system installed on site of the hydrogen power plant has been designed using the DiTemp® reading unit (delivered by Smartec/Sensornet). Each of four supply gas pipelines (one made of stainless steel with pure hydrogen to the fuel cell and three others made of carbon steel with waste hydrogen to power generators, Figure 4) is permanently monitored. The SHM system is based on distributed temperature measurements at the whole length. Distributed optical sensors were installed on the outer surface of the pipelines (on the top of each pipe). Sensor on the waste hydrogen pipelines were secured by protective coating (insulation layer and steel shield) and for pure hydrogen lines, they were secured only by aluminum tape.

Each temperature event connected with fuel leak (by Joule's-Thompson effect and/or medium-surroundings temperature difference) is detected and localized with a meter accuracy in approximately 40 seconds. The whole length of monitored pipelines is around 220 meters. Additionally ~400 meters of passive cables were installed. In case of any fuel leak an operator is alarmed and proper safety procedures are started.

a) b)

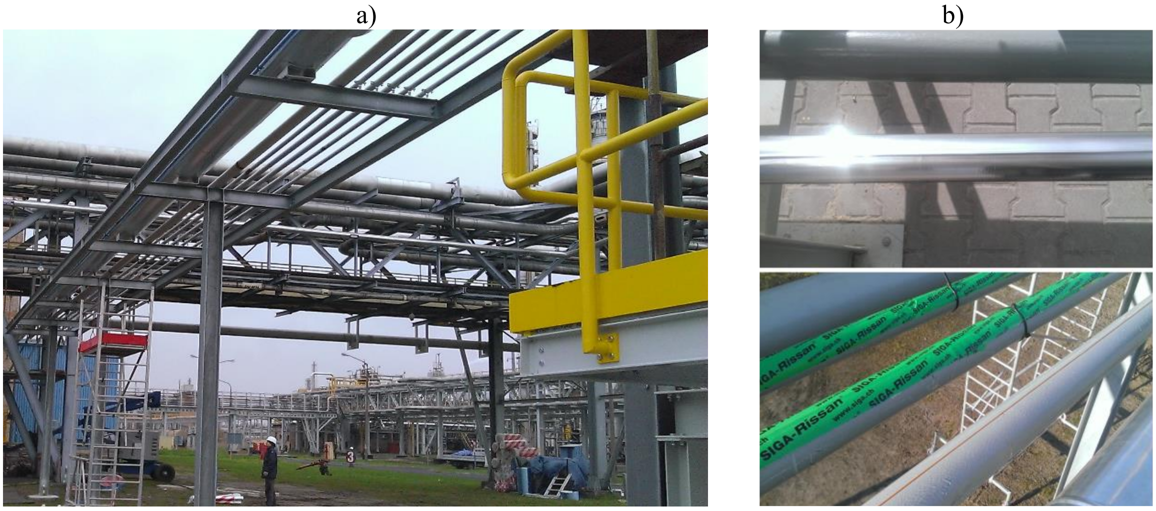


Figure 4: Hydrogen pipelines: general view (a) and view of the OFS sensors installed directly on the pure hydrogen and waste hydrogen pipelines (b)

Signals from the sensors are leaded to the control room (Central Measurement Point, CMP). It is located inside the power plant building. The DiTemp Light Reading Unit (measurement device) together with DiTemp Relay Switch are installed inside the rack. The DiTemp Module Relay Switch has 72 relay outputs. They allow for connection of alarm and warning signals to the main power plant control system. Furthermore this allows for full integration of the SHM subsystem with the management system of the hydrogen power plant. The measurement data are registered both: on the PC integrated with the DiTemp RU and on a dedicated database server. All devices are powered via an uninterruptible power supply (UPS). It allows, in case of problems with external power supply, keep running the whole CMP for a period of approximately one hour. Detailed view of the CMP is shown in Figure 5.

During the sensors installation a special attention was paid to control the quality of installation work. All the measuring heads were checked for quality, mechanical damage and markings, both before, during, and after installation. The control measurements were made using OTDR, laser as well as DiTemp RU. This allowed the immediate suspension of work in the case of any sensor failure, the emergence of unexpected problems and deviations from the plan, etc. The final stage of the installation of the measuring system was connection of all sensors to the reading unit in CMP and control (quality) measurements, which confirmed the correctness of the installation.

Reference measurements and calibration of the system were made during the initial start-up of the SHM system. On this basis it was possible to launch a dedicated software (DiView ®) and pass the system to power plant operator. Configuration of software for data acquisition and analysis was based on mapping of the sensors location in the system, and setting the alarm thresholds. Since the project is a R&D type, the work is still ongoing. In the further steps optimization of the pipelines monitoring strategy for a reliable evaluation and interpretation of data will be made.

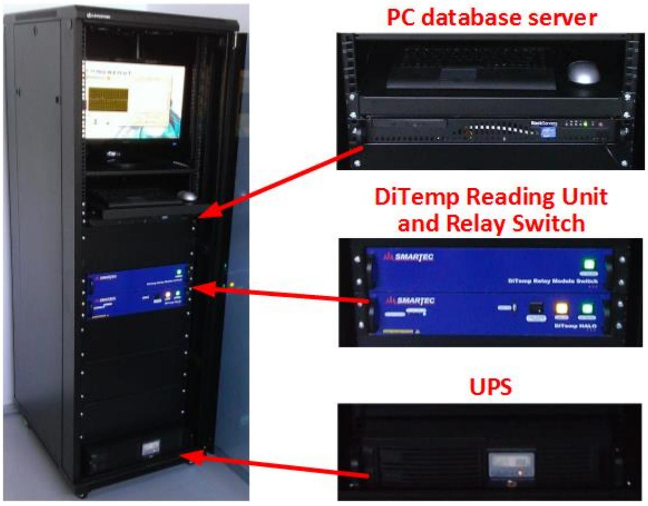


Figure 5: Central Measurement Point of the pipelines monitoring system

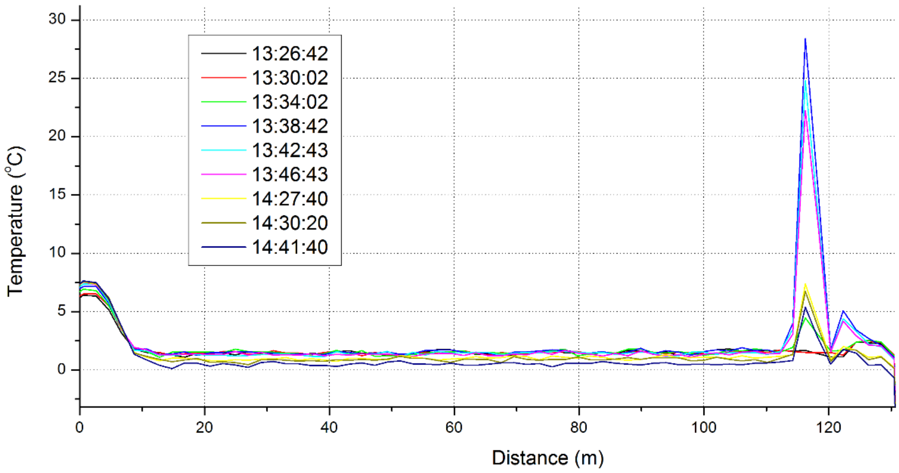
4 INITIAL MEASUREMENTS AND PROGRAMMED DEFECTS

As part of the preliminary research, taken before start of the hydrogen power plant, reference measurements were made. The selected results registered after sensors installation as well as during hydrogen generators operation are presented below.

Figure 6a shows the temperature distribution along the pipeline no 4. It was registered during the installation process and simulation of the local leak (so called programmed defect). The idea of this trial was to check the effectiveness of the leak detection system and correctness of their localization. For this purpose directly on the pipeline surface a water has been spilled. Its temperature was higher comparing to ambient temperature conditions (about 1.5 l @ 35 ^{0}C, ambient temperature ~ 2 ^{0}C). It is worth noting that local temperature at the distance of 117 m started to grow and temperature peak was easy to observe (local temperature anomaly). The temperature changes were clearly visible just in the next measuring cycle (after ~40 seconds) after leak.

Figure 6b presents the same programmed defect but this time the temperature difference in the following cycles were analyzed. It should be noted that this method of signal analysis eliminates the constant temperature components from temperature distribution profile and highlights the local events associated with sudden changes in temperature (leaks).

a)



b)

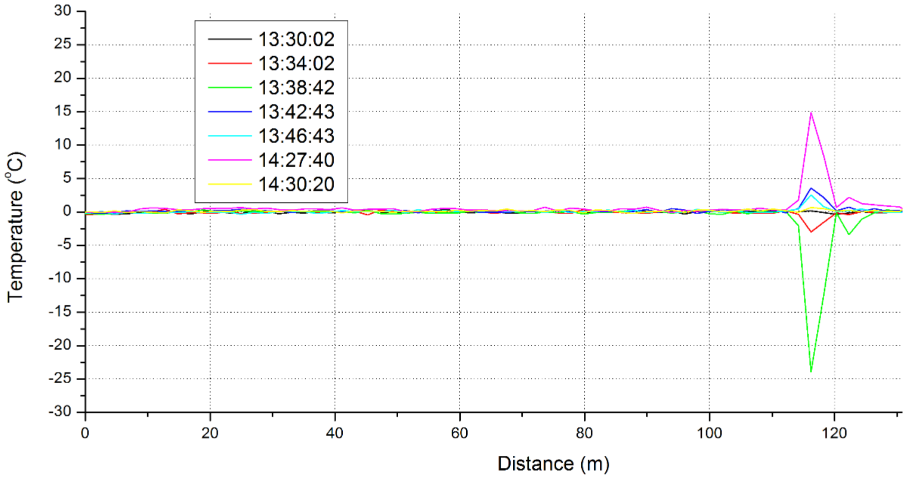


Figure 6: Testing of leak detection: raw temperature profile along monitored pipeline (a) and analysis of temperature changes by "leak detection algorithm" (b)

The temperature distribution along all hydrogen pipelines during the generators operation is presented in Figure 7. At this time generators were supplied from two sources: butyl (channel 3) and octyl alcohol loops (channel 4). It can be seen that upon the gas flow, the temperature of each of the supply pipelines increases (from the distance of 142 meters till the sensors end). Moreover, the temperature of the buffer pipeline (common pipe for all waste hydrogen sources; between 105 and 120 m), which at this distance is monitored by sensors connected to channels 2÷4, is also increasing.

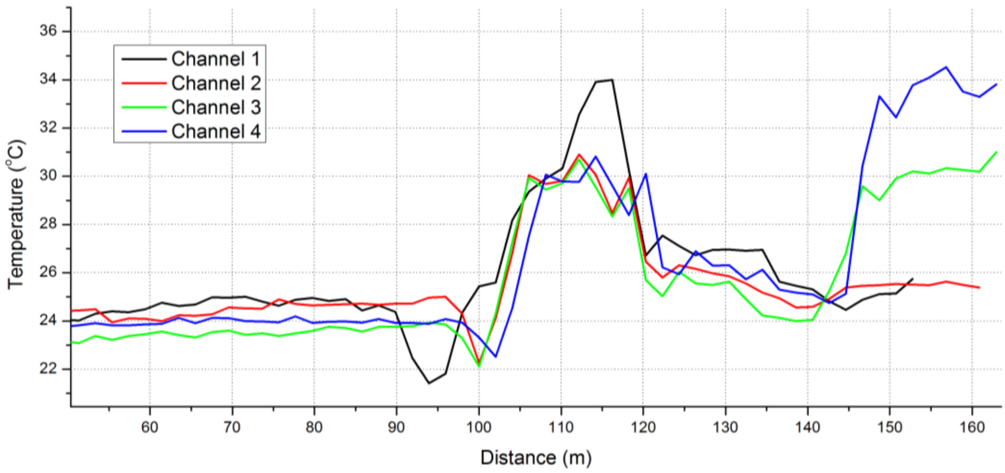


Figure 7: Temperature distribution along the pipelines during work of hydrogen generators

CONCLUSION

Presented solution of SHM system for dangerous goods pipeline monitoring is a first example of implemented system in industry area in Poland. That project has a demonstrative character, so it was planned to realize a full scale investigations in fields of waste hydrogen power generators and SHM systems for leakage detection. Preliminary tests with pipelines monitoring were done. It was shown that applied solution is able to detect potential failures in a short time (~40 seconds) and localize it with a sufficient accuracy (2 meters). In the next step it is planned to implement software with analysis module which will be able to online analyze measurement data in a reliable way and perform automatic detection of leaks.

ACKNOWLEDGMENT

This work is supported under grant POIG.01.04.00-02-105/10, co-financed by European Regional Development Fund (Poland, The Innovative Economy Operational Program 2007-2013, Action No 1.4).

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