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DIGITAL MODELS, SENSOR NETWORK AND AUTONOMOUS TELEMETRY MODULES FOR CRYOGENIC STORAGE SYSTEMS

E. S. Soldatov[1], volshebnoekoltso@mail.ru,
A. V. Bogomolov[2], a.v.bogomolov@gmail.com
[1]Research and production enterprise "Topaz", Moscow, Russian Federation,
[2]Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences, Moscow, Russian Federation

The article is devoted to organizational and technical aspects of remote monitoring the state of industrial systems, aimed at loss prevention during storage and transportation of cryogenic products. The necessity of research and development of new technical means for remote telemetry used in monitoring of the cryogenic tanks state is substantiated. The structure of a monitoring sensor network based on low-power autonomous LoRaWAN modules for cryogenic equipment of different types is presented. An algorithms for assessment the technical condition of the thermal insulation of a cryogenic tank have been developed. The first algorithm is used for assessing the state of the thermal insulation of a cryogenic tank by calculating the deviation of the pressure growth rate in the tank from the normal value. For cryogenic tanks, additionally equipped with a vacuum pressure sensor, a real-time calculation of the non-drainage storage of the product can be performed based on the measured value of the vacuum pressure in the heat-insulating cavity. Thus, the second algorithm is used for calculating the current estimate of the reserve time of non-drainage storage of the product in a cryogenic tank. A schematic diagram of an autonomous telemetry device for a tank container of different types based on a long-range module is described. A method is proposed and a device is described for monitoring the condition of cryogenic system elements using an unmanned aerial vehicles.

Keywords: LoRaWAN; sensor network; dangerous goods; monitoring of thermodynamic processes; non-drainage storage.

Introduction

In order to improve safety during the storage and transportation of dangerous liquid goods by various modes of transport (road, rail, air, river or sea), information systems for remote monitoring of the technical condition of the stationary and transport equipment are used [1–3]. At the same time, an urgent task today is the organization of long-term storage of cryogenic products (liquid oxygen, liquid nitrogen, liquefied natural gas (LNG), etc.) in stationary and transport systems, where the period of non-drainage storage of any of the listed substances is limited. This is due to a pressure rise in the tank because of the inevitable external heat flux from the atmosphere through the vacuum thermal insulation. In addition, the problem of pressure growth in a stationary storage system is getting worse due to the temperature stratification of the product, which occurs as a result of the natural convection process [4].

Each of the cryogenic storage systems, both stationary and transport, must be equipped with telemetry tools [5–7]. At present, at many facilities for the production and consumption of cryogenic products, telemetry systems use the calculation of the liquid level based on the measurement of the pressure difference in the vapor and liquid phases of the tank. The estimated values are obtained taking into account the correction for the change in density, calculated with data from the pressure sensor. The possibility of both local indication of parameters and data transfer to a remote device to control the process of non-drainage storage is provided. At the same time, to solve the problem of the lack of information for making decisions on reducing the loss of cryogenic products due to heat flux from the atmosphere, among other things, it is necessary to improve the existing telemetry tools. The key feature of the proposed technical solutions is the ability to take into account external storage conditions (for example, ambient temperature), as well as retrospective information about the storage process, which significantly affects the current forecast for the time of non-drainage storage of the product [8, 9].

1. Digital Models and Information System for Monitoring the State of Cryogenic Tank Equipment

Accurate prediction of the cryoproduct storage time in the tank using computational modeling is a complex task, the solution of which for the full range of probable thermodynamic states of the product is not yet possible. Therefore, to estimate the time of non-drainage storage of the product with sufficient accuracy for practical purposes, it is advisable to use heuristic computational algorithms [10]. At the same time, the task for the information system will be to provide remote monitoring of the state of cryogenic tank equipment, including the ability to calculate the reserve time of non-drainage storage of the product for each specific storage facility, based on the computational modeling results. Various storage systems can be included in the information monitoring system, regardless of the volume of the cryogenic storage or the distance between them.

The server of the digital twin (DT) of the storage system contains a computational complex where information is processed from the telemetry modules of each of the stationary and transport systems connected to the monitoring system. The key information is pressure and liquid level data. The information picture of the DT also displays the storage mode at a particular time (stationary or transport) and the main estimated parameter – the predicted time of non-drainage storage (Fig. 1).

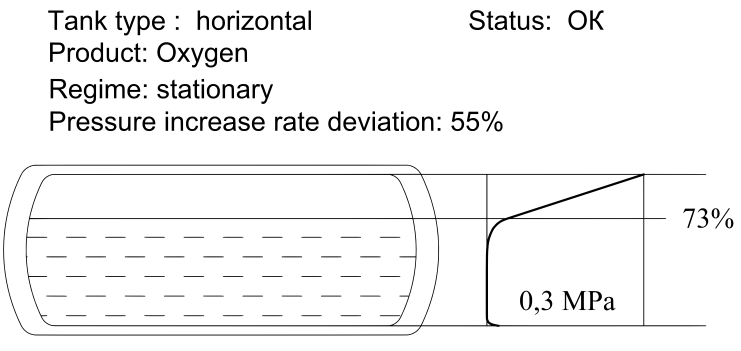

Fig. 1. Typical information picture for horizontal cryogenic tank

The basis for calculating the predicted time of non-drainage storage is an array of data on storage time obtained from the results of computational modeling and placed in a database (DB) of modeling results. The current information about the storage process is additionally recorded in the database of statistical information, which is subject to subsequent analysis in order to clarify the forecast of the storage time for a particular storage facility.

If necessary, the DT operator informs the storage system operator when the system status changes from “OK” to “ATTENTION” (the status changes if the storage time value becomes less than or equal to 24 hours). The storage system operator is also immediately informed when the status changes to “DANGER”. The status changes, for example, when the pressure in the tank reaches $0.98p_m$ (where p_m is the maximum allowable working pressure in the tank, or if the predicted value of the storage time becomes less than or equal to 2 h). Also the status changes in case of receiving an emergency message (the pressure value in the tank exceeds $1.15p_m$, the value of the liquid level in the storage exceeds 98%, there is no vacuum in the heat-insulating cavity, etc.).

2. On Technologies of Wireless Data Networks in Problems of Industrial Monitoring

The most interesting means of implementing the IoT concept for industry are networks such as LPWAN (Low-Power Wide Area Networks). An energy-efficient low-power long-range LPWAN network is designed to send small data packets, has a large number of connected devices that operate on batteries and do not require maintenance and recharging for a long period of time [11].

Among the practical options for implementing networks such as LPWAN, NB-IoT and LoRa technologies should be considered. The NB-IoT Narrowband Internet of Things is a cellular communication standard used for telemetry devices, making it easy to use in existing mobile communication systems. The advantages of NB-IoT technology are the huge network capacity (tens of thousands of connected telemetry devices), reduced power consumption and low cost of technical devices [12, 13].

LoRa (Long Range) is a wireless data network technology that provides long-range communication for autonomous devices with low power consumption, which uses the LoRaWAN link layer protocol [14, 15]. The LoRaWAN wireless data transmission network has a network architecture deployed in accordance with the “star of stars” topology, in which gateways transmit messages between end devices and the central network server [16–18]. Information about the storage parameters of the product is sent through the data transmission module to the cloud data storage and to the control center (Fig. 2).

Technical devices using LoRa technology have already been implemented as a means of remote monitoring of equipment for refueling vehicles with fuel based on liquefied petroleum gas (LPG) [19]. In particular, the use of the monitoring system allows obtaining real-time information on the level of fuel consumption and on the remaining fuel in all storage facilities connected to the system, which helps in planning the delivery of LPG, while reducing operating costs.

LoRa technology can also be effectively used for LNG storage and transportation, taking into account the specifics of storing substances at cryogenic temperatures.

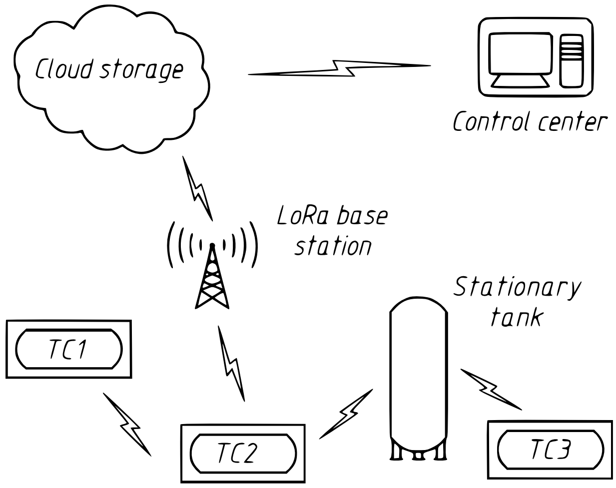

Fig. 2. Sensor network for monitoring the state of cryogenic equipment (TC1, TC2, TC3 – tank containers)

3. Computational Algorithms for Assessment the Current Condition of the Thermal Insulation of the Tank

Serially produced transport tanks and tank containers, as a rule, are not equipped with vacuum pressure sensors, which makes it impossible to assess the technical condition of the tank during operation. In other words, the vacuum level can only be measured when the tank is empty and out of service. Thus, without information about the parameters that affect the rate of pressure growth in a tank container, it is not possible to estimate the time of non-drainage storage of a cryogenic product. During long-term transportation and storage, when there is no consumption of a liquid product from the tank container, this can lead to losses due to automatic gas discharge through safety devices [20, 21].

For each transport tank or tank container with vacuum thermal insulation, discrete values of the liquid level in the tank are set and placed in the data array:

$$L = \{l_1,\ l_2, l_3, \ldots l_n\}.$$

In each case, the value of the liquid level corresponds to one or another value of the working pressure in the tank:

$$\forall l_j \in L \exists P_j = \left\{p_1^j, p_2^j, p_3^j, \ldots p_l^j\right\}.$$

The block diagram of the algorithm for assessing the state of the thermal insulation of a cryogenic tank by calculating the deviation of the pressure growth rate in the tank from the normal value is shown in Fig. 3. Obtaining information from sensors (converters) of pressure and level is carried out at the moment of time k.

In this case, the computational module rounds (upward) the values of pressure and liquid level to the nearest values from the above arrays, after which the nominal value of the pressure growth coefficient c_{nom} is uniquely determined for the current measured (rounded) values of pressure p_k and liquid level l_k. The array C of the nominal values of the pressure growth factor is predetermined by computer simulation methods or statistical methods and is located in the data storage unit. The deviation of the pressure growth rate

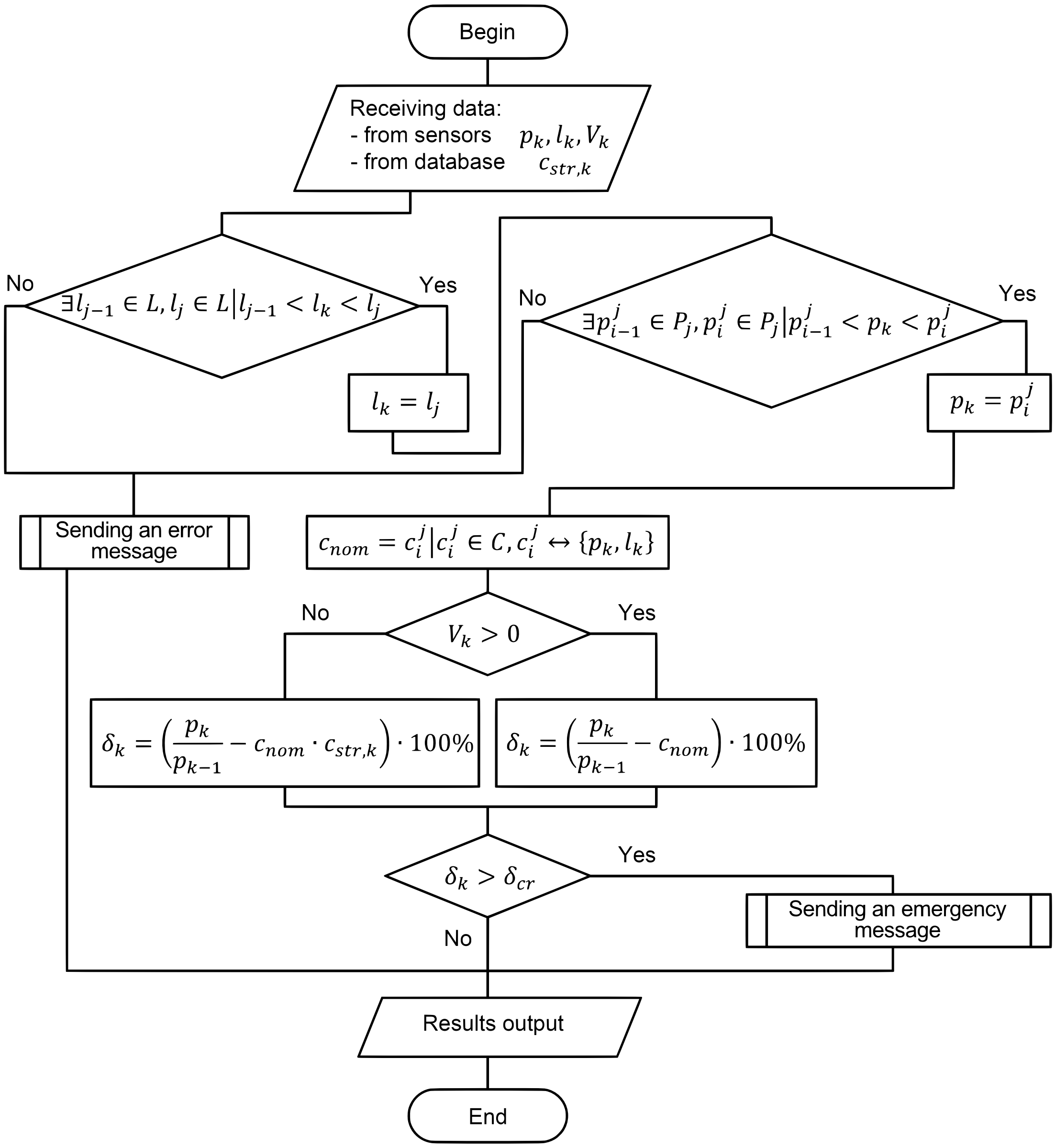

Fig. 3. Computational algorithm for condition assessment of the tank thermal insulation

from the nominal value is generally determined by the formula:

$$\delta_k = \left(\frac{p_k}{p_{k-1}} - c_{\text{nom}} \cdot c_{str,k}\right) \cdot 100\%,$$

where p_k is the current measured pressure value, p_{k-1} is the previous measured value, $c_{\text{str},k}$ is a coefficient that takes into account the degree of temperature stratification of the product. It is used only when calculating the stationary storage mode and depends on the geometric and operational characteristics of the tank container and at time k is loaded from the data storage unit with the simulation results. The mode of transportation (stationary or transport) is determined in accordance with the information from the navigation module by the current value of the speed of the container V_k.

If the deviation of the pressure growth rate exceeds the predetermined critical value δ_{cr}, an alarm message is generated and sent to the dispatch center. Receipt of an emergency message indicates a technical malfunction of the tank container, which led to a significant increase in vacuum pressure in the heat-insulating cavity. If necessary, information about a significant change in the technical condition of the tank container is sent from the operator's workstation to the driver of the vehicle or the operator of the operating organization. In this case, it becomes possible to take measures to prevent a further increase in pressure or to safely relieve pressure from the tank container.

For cryogenic tanks, additionally equipped with a vacuum pressure sensor, a real-time calculation of the non-drainage storage of the product can be performed based on the measured value of the vacuum pressure in the heat-insulating cavity. In other words, the inverse problem can be solved. The block diagram of the algorithm for calculating the current estimate of the reserve time of non-drainage storage of the product in a cryogenic tank is shown in Fig. 4. In this case, the key information is an array of storage time values U, also determined in advance by computer simulation methods or based on the processing of statistical data. Taking into account the measured value of the vacuum pressure $p_{v,k}$, the additional heat flow is calculated, which appears due to the leakage of gas into the heat-insulating cavity:

$$q_\beta = K_1 \cdot K_2 \cdot A_t \cdot p_{v,k}(T_k - T_{A,k}),$$

where K_1 is the coefficient that takes into account the fraction of gas molecules reaching the surface of the tank and exchanging thermal energy with the surface of the tank, K_2 is the coefficient that takes into account the thermodynamic properties of the gas, A_t is the surface area of the tank, $T_{A,k}$ is the temperature of the tank surface corresponding to the measured pressure in the tank p_k, T_k is the measured value of the ambient temperature.

Next, the external heat flow through the insulation qk is calculated, based on default value of the heat flow for the considered tank $q_{b,k}$ (as a rule, indicated in the technical documentation for the tank) and the base value of the ambient temperature $T_{b,k}$ at which it was calculated or measured the value of the base (passport) heat gain through the insulation.

Next, from the data array U in terms of storage time, the nearest storage time τ_{res} corresponding to the current value of heat gain q_k is selected. In case when the obtained value of the backup time of non-drainage storage τ_{res} is below the specified critical value τ_{cr}, an alarm message is also generated and sent.

4. Autonomous Telemetry Devices for Cryogenic Tank Equipment

Telemetry modules of stationary storage systems included in the sensor data network can serve as intermediate links in the chain of data transfer from modules of transport storage systems that are located at a considerable distance from the base station. Also, the sensor network itself for a large number of stationary storage systems for cryoproducts is a backup communication channel in case of absence of a connection to the main data network (for example, GPRS).

At the same time, for modern transport systems, in particular, for modules of cryogenic tank containers transported by different vehicles it is not possible to classically connect to a mobile data network. This causes the installation of autonomy telemetry modules

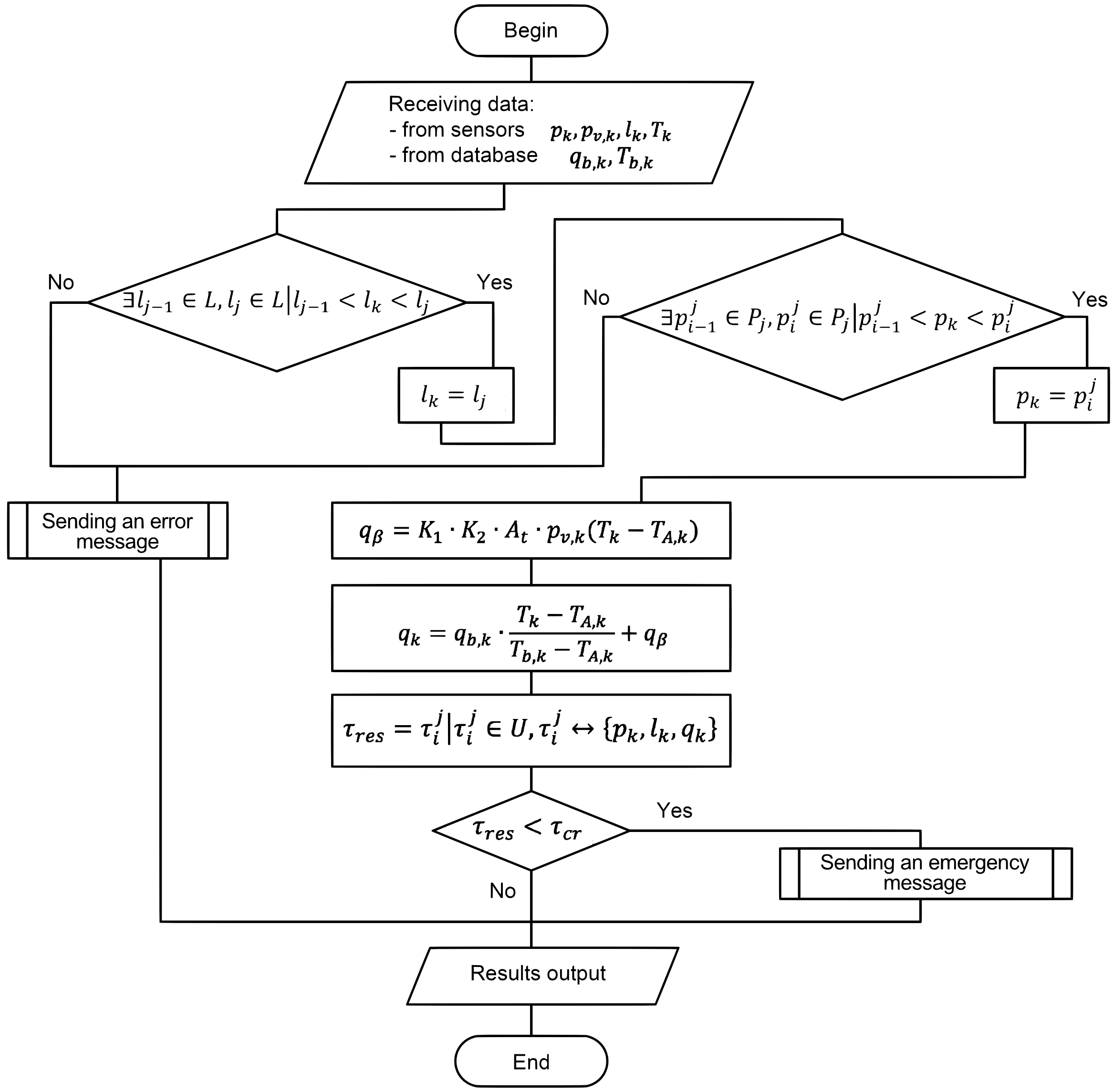

Fig. 4. Computational algorithm for storage time assessment by vacuum pressure deviation

on the container, which have low power consumption, but at the same time have a large communication range.

In the practical implementation of the data network concept for transport storage system, the chosen technology must provide reliable coverage for a large number of low-cost, low-power telemetry devices. For this purpose, sensor data transmission networks based on long-range modules, such as ZigBee Pro, NB-IoT or LoRaWAN modules can be used [22, 23].

A schematic diagram of proposed autonomous telemetry device based on the LoRaWAN module, designed to monitor the state of transport tank containers of various types, including cryogenic ones, is shown in Fig. 5.

Information exchange between the device blocks is carried out via the system bus. The controller processes information coming from the GPS/GLONASS receiver about the current coordinates and speed of the object.

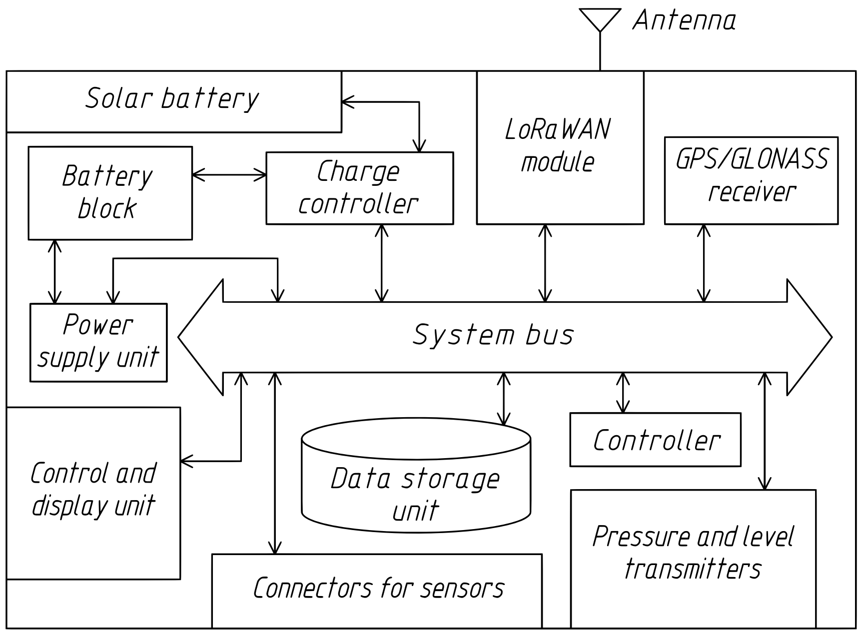

Fig. 5. Telemetry module for transport cryogenic equipment with autonomous power supply

The information panel of the control and display unit indicates the current values of the storage parameters: operating pressure, liquid level, approximate time of non-drainage storage. The device can operate on rechargeable batteries without maintenance and recharging for 1–2 years. Additionally, recharging of batteries from a solar battery can be arranged, which will further increase the period of continuous operation of the LoRaWAN module by several years.

Depending on type of transported product, the controller calculates the density of the liquid and the liquid level in the tank, in accordance with the current values of the vapor phase pressure and the pressure difference between the vapor and liquid phases of the tank, with subsequent recording in the data storage unit.

In addition, an estimated reserve storage time is calculated for the current values of pressure, liquid level and mode (transport or stationary). If the allowed values of storage parameters are exceeded, an alarm message is generated and sent [24].

In cases of storing cryogenic products at constant pressure in large-tonnage isothermal tanks with perlite thermal insulation, local violations of thermal insulation can lead to increased losses (perlite crumbles with time). Violation of the integrity of the vacuum thermal insulation of cryogenic pipelines also leads to additional losses or production halt. In these cases, a visual inspection of the outer surface of the equipment for the presence of frost is used, as well as more accurate and efficient diagnostics using a thermal imager [25].

However, diagnostics in most cases is extremely difficult due to the large dimensions of the tanks, as well as due to the location of cryogenic pipeline sections in places that are difficult to access for inspection, for example at high altitude. The number of objects for monitoring can reach several tens within one enterprise, or several hundreds within one industrial cluster.

In view of the foregoing, it is relevant to conduct regular diagnostics of the technical condition of tanks and pipelines using unmanned aerial vehicles (UAVs), which make it possible to remotely inspect equipment surface areas located in hard-to-reach places.

In particular, for the correct recognition of images of external icing on the equipment surface, obtained by a UAV using a camera, it is necessary to additionally control the current values of temperature and humidity of the environment. In addition, it is necessary to compare the obtained data taking into account climatic conditions that depend on the current date and current values of the GPS coordinates of the object.

Information exchange between module blocks is carried out via the system bus. In addition, all units are powered from the power supply through the system bus. When the UAV approaches the monitoring object at a given distance, information is read from the RFID tag. Information from the tag is used to identify a specific unit (tank, pipeline, etc.) and facilitate the subsequent search for a heat leak.

During the flight of the UAV along a given route, a stream of images from a thermal imager and a video camera is sent to the controller. Also, the controller receives information from the GPS/GLONASS receiver about the current coordinates, information from the navigation module about the flight altitude, as well as data about the current environmental conditions: information from the ambient temperature sensor and the outdoor air humidity sensor (Fig. 6).

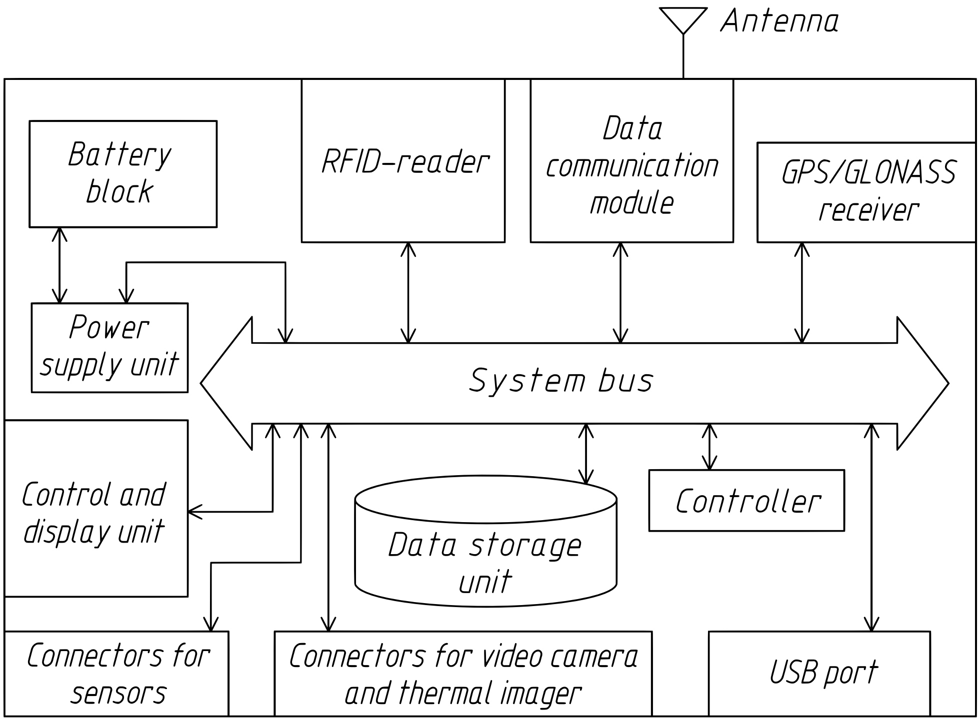

Fig. 6. UAV telemetry module for cryogenic equipment monitoring

The controller processes information coming from the thermal imager and video camera. In the process of recognition of materials, the selection of images received from the video camera, on which local icing of the surface is detected, is performed, followed by recording in the data storage unit. Also, images are selected with the distribution of the temperature of the surface of the equipment received from the thermal imager, in which areas with a temperature below the minimum allowable for a given object are found.

Information about the detected thermal leaks is sent to the data storage unit, from where, if necessary, it is possible to overwrite it on a removable media connected to the device via a USB port. In case of using the UAV in semi-automatic mode, real-time information is sent to the dispatch center for monitoring and control through the data communication module. The control and display unit also provides a function to control the preview of images recorded in the data storage unit.

The proposed telemetry device can be used as part of a UAV in any subject area where it is necessary to detect and determine the exact location of thermal leaks recorded using a thermal imager or video camera.

Conclusions

Thus, through the use of autonomous energy-efficient telemetry modules, transport cryogenic tank containers can be included in the information system for monitoring the state of cryogenic equipment.

Using of the proposed information system ensures providing information to responsible persons on the parameters of non-drainage storage of cryogenic products in real time. This allows taking measures in time to prevent product losses during storage, as well as to prevent the occurrence of an explosive and fire hazardous situation.

Additional studies require problems associated with the use of frost-resistant batteries in telemetry modules when equipment is operating in harsh climatic conditions, as well as roaming problems when moving from one sensor network to another, which is important when tracking cryoproducts shipments over long distances.

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Evgeniy S. Soldatov, Phd (Tech.), Senior Researcher, Research and Production Enterprise "Topaz" (Moscow, Russian Federation), volshebnoekoltso@mail.ru

Alexey V. Bogomolov, DSc (Tech.), Professor, Leading Researcher at the Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences (Moscow, Russian Federation), a.v.bogomolov@gmail.com

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ЦИФРОВЫЕ МОДЕЛИ, СЕНСОРНЫЕ СЕТИ И АВТОНОМНЫЕ ТЕЛЕМЕТРИЧЕСКИЕ МОДУЛИ КРИОГЕННЫХ СИСТЕМ ХРАНЕНИЯ

Е. С. Солдатов, А. В. Богомолов

В статье рассмотрено математическое и организационно-техническое обеспечение дистанционного мониторинга состояния промышленных криогенных систем хранения, задачей которых является предотвращение потерь криогенных продуктов при хранении и транспортировке. По результатам анализа потребностей практики обоснована необходимость исследования и разработки технических средств телеметрии, используемых для дистанционного контроля состояния криогенных систем хранения. Представлена структура сенсорной сети мониторинга на базе энергоэффективных автономных модулей LoRaWAN, применимой для криогенного оборудования различного типа. Разработаны алгоритмы расчета оценки технического состояния теплоизоляции криогенного резервуара, позволяющие получить такую оценку по величине расчета отклонения скорости роста давления от нормального значения, а также рассчитать оценку резервного времени бездренажного хранения продукта в криогенном сосуде в режиме реального времени на основе измеренного значения давления вакуума в теплоизоляционной полости сосуда. Описана принципиальная схема автономного устройства телеметрии танк-контейнера на базе модуля телеметрии дальнего действия. Предложен метод и описано оригинальное устройство контроля состояния криогенной системы с помощью беспилотного летательного аппарата. Использование результатов исследования обеспечивает предоставление ответственным лицам информации о параметрах бездренажного хранения криогенной продукции в режиме реального времени для своевременной выработки и реализации мер по предотвращению потерь криогенных продуктов при хранении, а также для минимизации рисков взрыво- и пожароопасных ситуаций.

Ключевые слова: LoRaWAN; сенсорная сеть; опасные грузы; мониторинг термодинамических процессов; бездренажное хранение.

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Солдатов Евгений Сергеевич, кандидат технических наук, старший научный сотрудник, Научно-производственное предприятие «Топаз» (г. Москва, Российская Федерация), volshebnoekoltso@mail.ru

Богомолов Алексей Валерьевич, доктор технических наук, профессор, ведущий научный сотрудник, Федеральный исследовательский центр «Информатика и управление» РАН (г. Москва, Российская Федерация), a.v.bogomolov@gmail.com

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