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INFORMATION PROCESSING ALGORITHMS IN TASKS OF MONITORING AND PREDICTING THE STATE OF CRYOGENIC EQUIPMENT

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The article discusses the issues of collecting, processing and transmitting information during remote monitoring of the condition of stationary and transport cryogenic equipment used for long-term storage of cryogenic products. A solution to the problem of preventive informing dispatch services and the operating organization about the presence of a technical malfunction of a cryogenic vessel is outlined, which leads to an increase in vacuum pressure in the thermal insulation cavity, which causes an increased heat flow from the environment and a significant change in pressure in the internal vessel over time. The structure of the information system for monitoring the condition of cryogenic equipment is presented and a description is given of the computational algorithm for calculating the assessment of the technical condition of the screen-vacuum thermal insulation of a cryogenic vessel based on the deviation of the pressure growth rate, as well as the algorithm for calculating the assessment of the time of drainless storage taking into account changes in vacuum pressure in the heat-insulating cavity.

Keywords: computational algorithm; cryogenic equipment; equipment monitoring; remote monitoring; drainless storage.

Introduction

During long-term storage of cryogenic products (liquid oxygen, liquid nitrogen, liquefied natural gas, liquid hydrogen, etc.) with a closed gas release valve (drainless storage), heat inflows through vacuum thermal insulation lead to evaporation of part of the product and an increase in pressure in a vessel of any type: reservoir, tank , fuel tank, etc. The problem is aggravated when, for various reasons, there is no selection of liquid product from cryogenic vessels for consumer needs for a long time, in particular, when the lack of selection is due to the need for long-term storage of fuel at enterprises [1–3]. As a rule, this leads to product losses after the maximum permissible operating pressure in the vessel is reached due to the automatic release of gas to the atmosphere through safety valves. In this case, the level of loss of the cryogenic product is directly related to the technical condition of the vessel, mainly with the magnitude of the vacuum pressure in the thermal insulation cavity of the reservoir, tank or fuel tank. Leaks of flammable gas vapors also lead to the formation of an explosive cloud in the air of the working area, which is difficult to dissipate due to the active condensation of atmospheric moisture, which causes increased risks of an explosion and fire situation [3–6].

Diagnostics of the thermal insulation of a cryogenic vessel is difficult due to the absence in most cases of stationary vacuum pressure sensors. This necessitates stopping the vessel and temporarily taking it out of service to assess the state of the thermal insulation [7, 8]. At the same time, it is possible to obtain an assessment of the technical condition of the vessel using indirect methods, for example, by calculating the rate of pressure growth, which in the general case is nonlinear. In this case, it is advisable to use digital twins of a cryogenic storage system (CS), which use databases of the results of computer modeling of drainless storage processes for various cryogenic products [8–11]. However, accurately predicting the storage time of a cryogenic product in a CS using modeling is a complex task, the solution of which for the entire range of probable thermodynamic states of the product is not yet possible [12]. Therefore, to calculate an estimate of the time of non-drainage storage of a product with sufficient accuracy for practical purposes, it is advisable to use heuristic computational algorithms [13, 14].

1. Information System for Monitoring the Condition of Cryogenic Equipment

The basic task of information interaction in the «storage system – digital twin» connection is to provide remote monitoring of the condition of cryogenic equipment, including the ability, based on the results of computer modeling, to calculate the reserve time for drainless storage of a product for each specific storage system [15–19].

A block diagram showing the relationship of software tools when solving problems of industrial monitoring of the condition of cryogenic storage systems is shown in Fig. 1. Information from sensors and converters is sent to the telemetry module. Due to the presence of an individual telemetry module in each of the storage systems, the state of which is monitored in real time, various storage systems can be included in the information monitoring system, regardless of the volume of cryogenic storage or the distance of the systems from each other [20, 21].

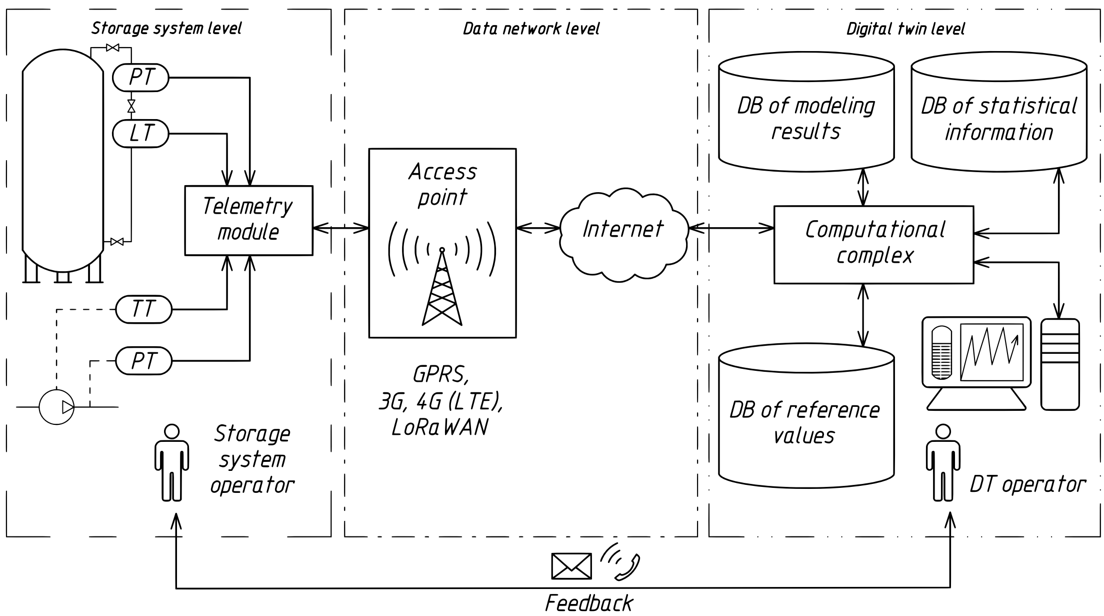

Fig. 1. Structure of the information system for monitoring the condition of cryogenic equipment (CS – storage system; DB – database; CD – digital twin; PT, LT, TT – transducers, respectively, pressure, level and temperature)

The digital twin (CD) server of the storage system contains a computing complex where information received from the telemetry modules of each of the stationary and transport storage systems connected to the monitoring system is processed. The key information is data on the pressure and level of the liquid product. The information picture of the CD also displays the storage mode at a specific point in time (stationary or transport) and the main calculated parameter – the estimate of the reserve time of drainless storage.

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

Algorithm for calculating the assessment of the current technical condition of a cryogenic vessel. For each storage tank with vacuum thermal insulation, discrete values of the liquid level in the vessel are specified and placed in a data array

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

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

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

The block diagram of the algorithm for calculating the assessment of the state of thermal insulation by calculating the deviation of the rate of increase in pressure in the tank from the normal value is shown in Fig. 2. Information is received from pressure and level sensors (transducers) at time k.

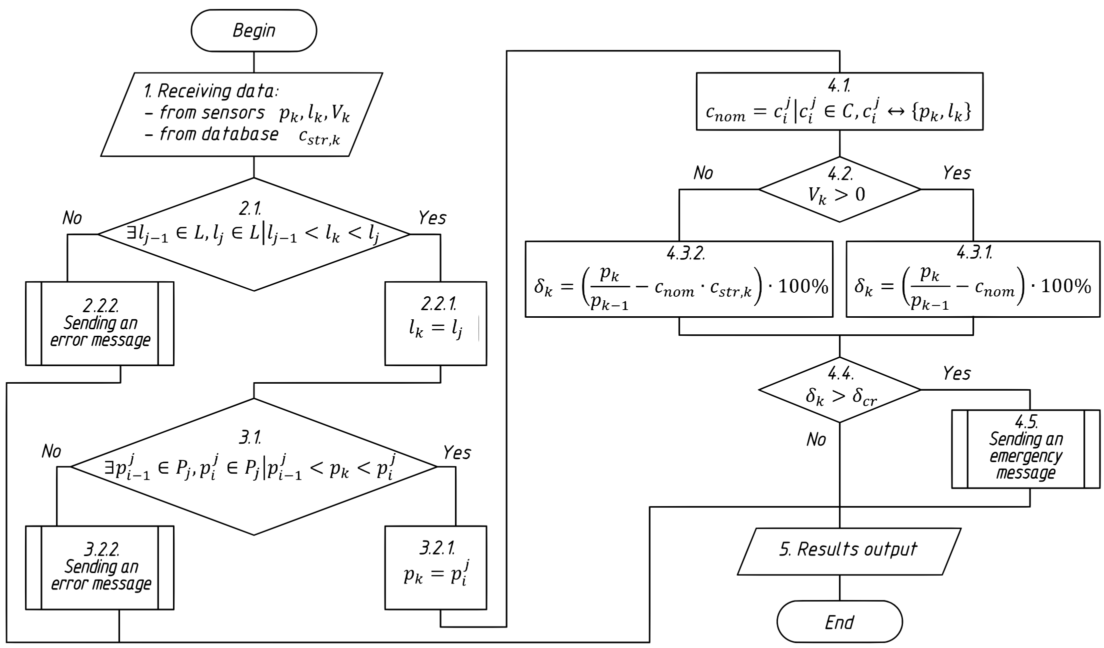

Fig. 2. Algorithm for calculating an assessment of the current technical condition of a vessel based on changes in the growth rate of cryoproduct pressure

In this case, the computational module rounds (up) 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 nominal values of the pressure growth coefficient is determined in advance by computer modeling or statistical methods and is located in the data storage unit.

The deviation of the pressure growth rate from the nominal value is generally determined by the formula:

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

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

If the deviation value of the pressure growth rate exceeds the specified critical value δ_{cr}, an emergency message is generated and sent to the CD operator. Receipt of an emergency message indicates a technical malfunction of the CS, which led to a significant increase in vacuum pressure in the heat-insulating cavity. If necessary, the storage operator is informed about a significant change in the technical condition of the vessel or the driver of the vehicle is notified in the case of a tank. Thus, it becomes possible to take measures to prevent further increase in pressure or to safely relieve pressure from the cryogenic vessel.

2. Algorithm for Calculating the Estimate of Reserve Time for Non-Drainage Storage of a Product in a Vessel

For cryogenic vessels additionally equipped with a vacuum pressure sensor, a real-time calculation of drainage-free product storage can be performed based on the measured vacuum pressure value in the thermal insulation 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 for non-drainage storage of a product in a cryogenic vessel is presented in Fig. 3.

In this case, the key information is an array of storage time values U, also determined in advance by computer modeling methods or based on processing statistical data [14, 22, 23]. Taking into account the measured value of vacuum pressure $p_{v,k}$, the additional heat flow resulting from gas leakage into the heat-insulating cavity is calculated:

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

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

Next, the heat flow from the environment through the insulation q_k is calculated based on the base value of the heat flow for the vessel in question $q_{b,k}$ (usually indicated in the

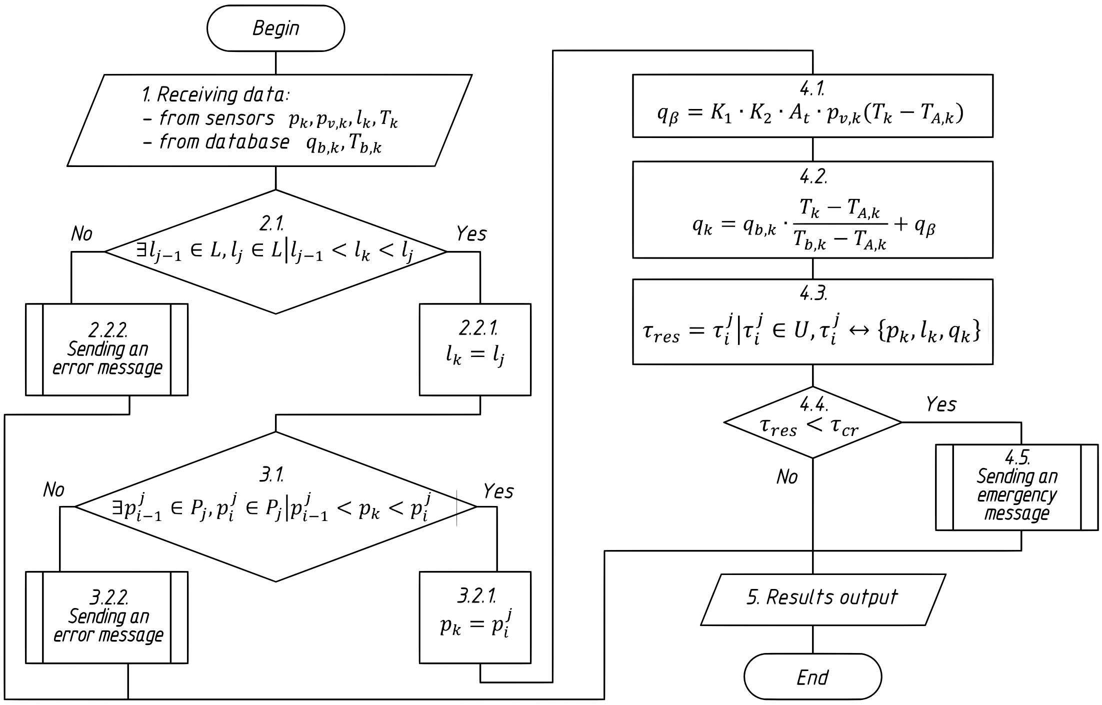

Fig. 3. Algorithm for calculating the time of non-drainage storage, taking into account changes in vacuum pressure in the thermal insulation cavity

technical documentation for the vessel) and the base value of the ambient temperature $T_{b,k}$ at which it was calculated or measured the value of the basic (certified) heat flow through the insulation. Next, from the data array U in terms of storage time, the storage time τ_{res} that is closest in value is selected, corresponding to the current value of heat inflow q_k. In the case when the received value of the reserve time of non-drainage storage τ_{res} is below the specified critical value τ_{cr}, an emergency message is also generated and sent.

Conclusion

The use of an information system for remote monitoring and forecasting of the condition of cryogenic capacitive equipment is justified by the growing needs for technical gases, including liquid cryogenic fuel, as well as the increase in the required storage time of fuel reserves at enterprises. The developed heuristic computational algorithms make it possible to timely calculate the assessment of the technical condition of thermal insulation of cryogenic equipment. The application of the proposed solutions can significantly improve the safety of operation of cryogenic vessels of various types, due to preventive information about changes in the technical condition of the vessel during operation, which allows, in particular, to prevent the occurrence of leaks and prevent the formation of explosive mixtures in the air.

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АЛГОРИТМЫ ОБРАБОТКИ ИНФОРМАЦИИ В ЗАДАЧАХ КОНТРОЛЯ И ПРОГНОЗИРОВАНИЯ СОСТОЯНИЯ КРИОГЕННОГО ОБОРУДОВАНИЯ

Е. С. Солдатов

В статье рассмотрены вопросы сбора, обработки и передачи информации при дистанционном контроле состояния стационарного и транспортного криогенного оборудования, применяемого для длительного хранения криогенных продуктов. Изложено решение задачи превентивного информирования диспетчерских служб и эксплуатирующей организации о наличии технической неисправности криогенного сосуда, которая приводит к увеличению давления вакуума в теплоизоляционной полости, что обусловливает повышенный теплоприток из окружающей среды и существенное изменение давления во внутреннем сосуде с течением времени. Представлена структура информационной системы мониторинга состояния криогенного оборудования и приведено описание вычислительного алгоритма расчета оценки технического состояния экранно-вакуумной теплоизоляции криогенного сосуда по отклонению темпа роста давления, а также алгоритма расчета оценки времени бездренажного хранения с учетом изменения давления вакуума в теплоизоляционной полости.

Ключевые слова: вычислительный алгоритм; криогенное оборудование; мониторинг оборудования; дистанционный мониторинг; бездренажное хранение.

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