Decision Support Models and Algorithms for Remote Monitoring of the Equipment State

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Abstract. The article describes some problem aspects of monitoring the operational regimes of the remote equipment: stationary and transport cryogenic tanks. A functional structure is presented that demonstrates interconnection of programs for modeling heat and mass transfer processes, a computational modules and programs for monitoring the state of stationary and cryogenic tanks of various types. The main advantages of using the considered models and algorithms for remote monitoring and controlling are the possibilities of taking into account the changing of different operational regimes for cryogenic equipment, variable ambient temperature, as well as the technical condition of the screen-vacuum superinsulation. An example of a decision support algorithm for controlling operational regimes of cryogenic tanks with a volume of up to 70 cubic meters is considered. The effectiveness of the proposed models and algorithms is confirmed by the results of software testing according to experimental data obtained during multimodal transportation of cryogenic products by various types of transport.

Keywords: Remote monitoring, Decision support algorithm, Cryoproduct, Holding time, Cryogenic tank, Liquefied natural gas.

1 Introduction

The main problem aspect need to be taken into account in monitoring and controlling the remote cryogenic equipment is frequently changing operational regimes of stationary and transport tanks [1-3]. The more important independent factors influencing the value of time until the end of the non-drainage storage process of the cryoproduct are the degree of thermal stratification, the value of the heat flux through the screen-vacuum superinsulation, and the influence of vibrations of the tank during the transportation [4-6].

Lack of adequate information about the current parameters of the cryoproduct in the tank can lead to making the incorrect decisions by the personnel responsible for the remote control of the equipment [7-8]. The pressure increasing in the tank jointly with a small product consumption can eventually lead to undesirable gas losses due to discharge through safety valves and in the case of storage of flammable cryoproducts (e.g. liquefied natural gas, ethylene) create explosive mixtures in air and cause fire hazardous situations [9-15].

2 Materials and methods

2.1 About a formal statement of the problem of controlling the operational regimes of the remote equipment

The main task in controlling the operational regimes of cryogenic tanks is to achieve the maximum drainage free holding time, which is ensured by regulation of the pressure in the gas phase p_s with the help of discharge valves (Fig. 1), as well as switching to product delivery from the gas phase, instead of delivery from the liquid phase, and vice versa (if technically possible), at a given maximum working pressure in the tank p_{max}. Therefore, as the objective function is considered drainage free holding time of the cryoproduct τ_H (the holding time) [16-19].

Based on practical experience in operation of stationary and transport cryogenic tanks [20-23], it makes sense to consider the holding time as a function of the following independent parameters:

$$\tau_H = f\left(p_s, p_f, p_{vac}, T_0^m, A_l, f_l, A_{tr}, f_{tr}\right) \rightarrow \max \quad (1)$$

Where p_f, p_s – current values of pressure in, respectively, liquid and vapour phase of the tank, T_0^m – current measured value of outside air temperature, p_{vac} – pressure in the vacuum space (optional), τ_H – the holding time. For transport tanks with appropriate mechanical sensors can be taken into consideration amplitude A_l, A_{tr} and frequency f_l, f_{tr} of, respectively, longitudinal and transverse vibrations of the tank.

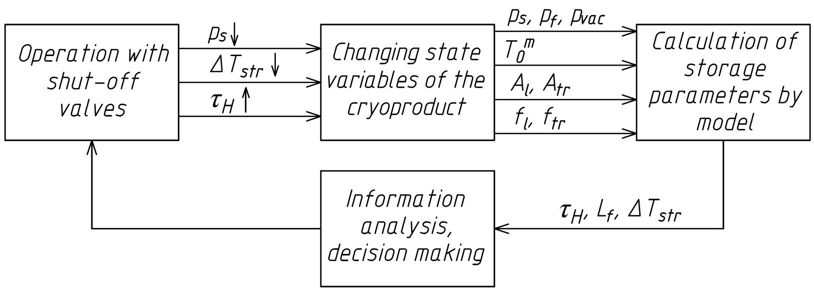

Fig. 1. Control scheme of cryoproducts storage regimes (ΔT_{str} – temperature stratification, L_f – level of liquid in the tank).

With such a formulation of the problem, especially given a lot of random parameters, it is impractical to compile a general analytical expression for the objective function. To solve the problem of maximizing the holding time, a decision support algorithm for predicting drainage free holding time of the cryoproduct was developed.

2.2 Structure of decision support system for controlling the operational regimes of cryogenic tanks

To improve information support of operators, it is proposed to use decision support system for controlling the operational regimes of cryogenic tanks. The functional scheme of the considered system support system is shown in Fig. 2. The based information for evaluation of the pressure in the vapour phase of tank and predicted holding time is the results of computational modeling, obtained in universal software complex ANSYS Fluent. A several two-dimensional computer models were prepared to calculate temperature and pressure fields for heat and mass transfer processes in cryogenic tank [24-27].

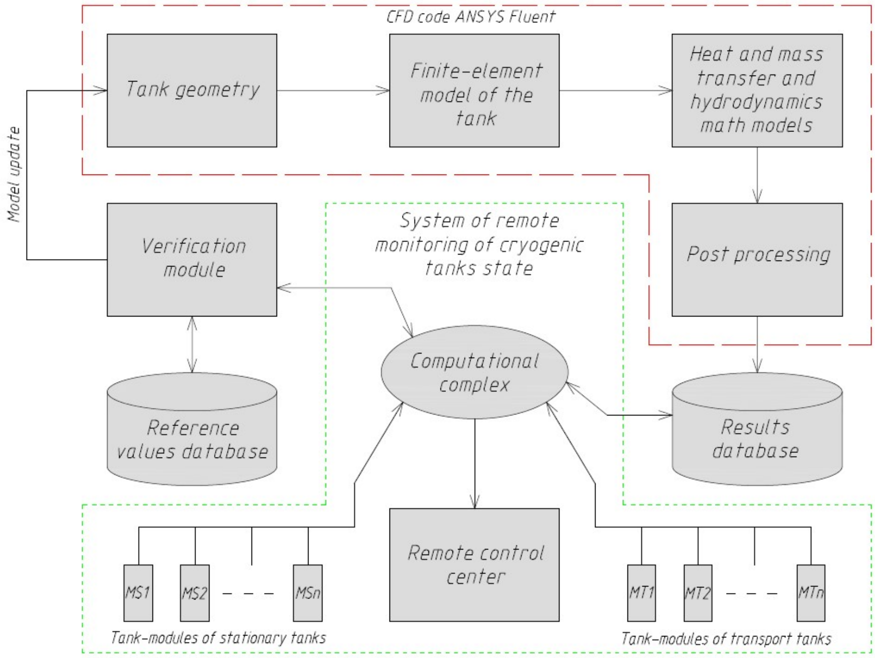

Fig. 2. Decision support system for controlling the operational regimes of cryogenic tanks.

A database of the main parameters of the simulation results is being accumulated, as new data on the geometric and operational characteristics of stationary and transport tanks (including tank containers), thermodynamic components (including mixtures) are accumulated. From this information, upon request from the computing module, an array of values of tank gas pressure and holding time data is formed, from the elements of which the required value of the predicted drainage free holding time is subsequently determined (Fig. 3).

Remote control center accumulates information from the tanks: data on the pressure and level of the liquid product, technical condition of the thermal insulation, the current storage regime (stationary or transport), the predicted holding time.

3 Results

3.1 Decision support algorithm for predicting the holding time

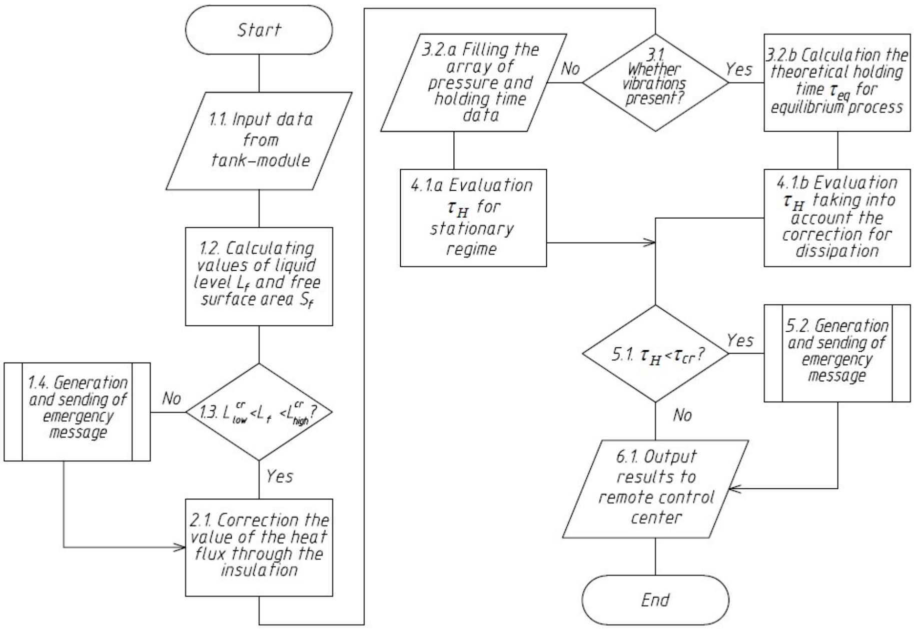

Fig. 3. Decision support algorithm for predicting the holding time.

The algorithm described in this subsection allows one to consider stationary and transport cryogenic tanks for various purposes with a volume of up to 70 m^3.

Optionally having a current value of the vacuum pressure p_{vac} obtained from the mechanical vibration sensors, the calculation of the additional heat gain due to the gas in the inter-tank space may be written as follows:

$$Q_{gas} = \alpha \left(\frac{k+1}{k-1} \right) \frac{18{,}2 p_{vac}}{\sqrt{\mu T_0}} \left(T_0^m - T_c \right) F_c \qquad (2)$$

Where F_c – the evaluated area of the cold wall of the tank, T_c – the temperature of the cold wall of the tank, μ – molecular weight of the cryogenic product, k – adiabatic Poisson's ratio, α – the energy accommodation coefficient. The evaluated heat gain through the superinsulation Q_{ins} is calculated as follows:

$$Q_{ins} = \frac{T_0^m - T_c}{T_0 - T_c} Q_{db} + Q_{gas} \quad (3)$$

Where T_0*=293 K (0 °C)* – normal temperature, Q_{db} – the returned value of the heat gain through the superinsulation of the tank from the main database.

For a stationary mode the data array of time $\tau_{H,i}$ and storage pressure p_j corresponding to the previously calculated heat flow is loaded into the computing module. If the obtained value of τ_H turns out to be less than the specified value of the critical pressure τ_{cr}, the system generates and sends an emergency message to the remote control center.

3.2 Typical information picture and operator's decisions

Based on current tank-state information picture (Fig. 4), the operator responsible for remote monitoring of the state of cryogenic tanks can make decisions for:

- sending a message to the technical gases logistics service about the need to refuel the tank (when the liquid level drops below 30%, if the tank is used in stationary storage mode);
- informing the responsible person when changing the status to "ATTENTION" (the status changes if the value of holding time becomes less than 24 hours);
- immediately informing the person responsible for the good condition and safe operation of the tank and special services (if necessary) in case of an emergency message (the pressure in the tank exceeds 1,15 of maximum, there is no vacuum in the heat-insulating cavity, the liquid level exceeds 98 %, etc.).

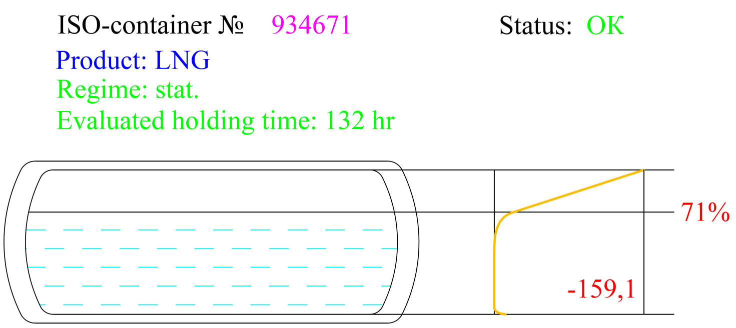

Fig. 4. The example of information picture on the state of a cryogenic tank on the operator's display of remote control center.

3.3 Computational results and software testing by empirical data

For analyzing the correspondence between the calculated and passport values of the holding time, some experimental data concerning storage of cryogenic products (nitrogen, argon, liquefied natural gas and ethylene) in multimodal transport units (40 000 litres volume ISO-containers) were considered (Fig. 5).

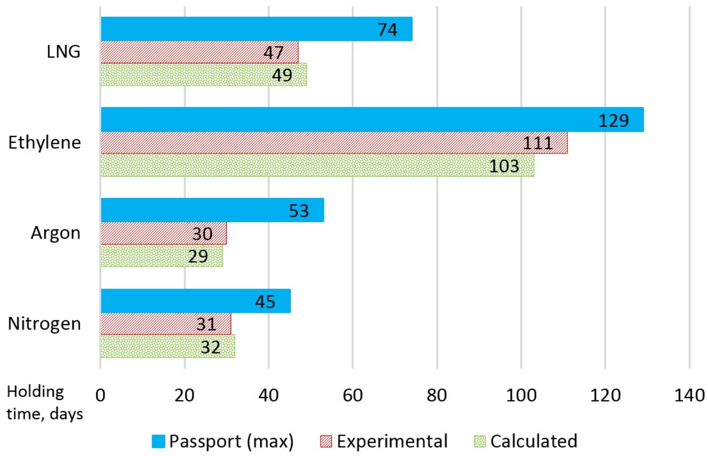

Fig. 5. Evaluated and experimental long-term storage parameters of cryogenic products in a multimodal ISO-container (40 000 litres volume).

4 Discussion

For the consideration, the total holding time for one multimodal transport unit was evaluated. The holding time from the initial minimum pressure to the maximum allowed pressure 0.7 MPa was considered .

As shown in comparison diagram (Fig. 5), the evaluated and experimental values of the holding time turn out to be significantly lower than the maximum theoretical values (passport theoretical holding time values) for ISO-containers. The results of the calculations of the operational parameters differ from the experimental values by no more than 3 ... 5 %, which makes it advisable to predict the safe holding time based on the results of computational modeling.

5 Conclusion

The research describes some features of estimation the key characteristics of stationary and transport cryogenic tanks, namely: the time of drainage free holding time and level of liquid – for various regimes of storage.

The advantages of the decision support system for monitoring the state of stationary tanks, cisterns and ISO-containers were presented. An algorithm for calculating the non-drainage holding time makes it possible to predict both stationary and transport operational values, which allows to make timely operational decisions on storage and transportation regimes of remote cryogenic equipment. Validation results on the non-drainage holding time by empirical data, obtained in the process of multimodal transportation of cryoproducts, showed that the calculated data differ from the empirical values by no more than 5 %. The introduction of the proposed monitoring system for a specific fleet of stationary and transport cryogenic tanks will significantly increase the safety of operation by ensuring technological processes without venting flammable gases into the atmosphere.

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