The concept of building training systems for training operators of liquefied hydrocarbon warehouses

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Abstract. The article deals with the concept of building computer training complexes as one of the effective aids for ensuring the safety of potentially dangerous technological processes which include the storage and transportation of liquefied hydrocarbon gases. The authors have developed and described simulator model of one of the key technological devices for the storage of liquefied hydrocarbons which underlies the proposed software platform for the synthesis of training simulator systems.

1. Introduction
Under Federal Law No. 116 «On industrial safety of hazardous production facilities» [1], the storage and transportation of combustible and explosive substances which include liquefied hydrocarbon gases (LHG) are classified as hazardous production facilities of the 1st class. Organizations operating such facilities are required to have the control systems of industrial safety and ensure their functioning. In the framework of the implementation of this law organizations are required to train employees in the event of an accident or incident at a hazardous production facility in accordance with the developed plan for emergency localization and elimination accidents as well as conduct their periodic certification in the field of industrial safety.

Moreover under order No. 96 of the Federal Service for Ecological, Technological and Nuclear Supervision of March 11, 2013 [2] all workers and engineering and technicians directly involved in the technological process and the operation of equipment at these facilities should undergo the training using modern technical training aids for acquiring the practical skills for the safe execution of work, the prevention of accident and elimination of their consequences on the technological facilities with blocks of 1 category of the explosive hazards. Operator training simulators (OTS) are one of such a way. Under this document the training and the improvement of practical skills at OTS should ensure improvement of the technological process and control system, start-up, scheduled and emergency stop in typical and specific emergency and accidents. The main goal of the OTS is the acquisition and the maintenance of professional competencies of workers of the hazardous production facilities at the level necessary for the timely and error-free elimination of a potential accident or the threat of its occurrence. Computer training complexes meet the requirements of the law by the fact that they allow forming competences of safe production management for staff in a group or individually [3].
One of the practical aspects of the OTS design is the compliance of its content with the production requirements from the point of view of the tasks of personnel training and quality control of vocational training. During the development it is also required to take into account the possibility of changing customer requirements for the modeling object as well as training tasks. [4].

![Functional scheme of the simulation on the OTS Platform.](image)

A modeling platform is required to implement a systematic approach to the development of training systems as an ecosystem. The platform should play the role of a design simulator, allowing developers to design a mathematical description, using libraries of model components of a chemical and technological system (CTS) in real time. Also the platform should minimize the time spent on developing the model and reducing the number of errors. However, in the scientific literature the issues of building modeling platforms are poorly covered and the platforms themselves are the intellectual property of large developers.

The concept assumes that two types of components form the OTS platform: a simulation server and clients of emulators of trainee operators of workplaces (SCADA simulators, interactive technological schemes and interactive emulators of field equipment and so on).

The simulation server implements the core of the OTS platform based on a stream independent application. When connecting via a client’s calculating network and requesting the training exercises the platform generates an isolated instance of the training simulator model, initializes it with initial conditions, splits the model calculation process into program flows, activates and manages the model calculation (starting, stop, pause and speed up of the count).

The structure of the training simulator model implements three types of mathematical descriptions: Technological Process Models (TPM), Control System Models (CSM) and Safety system Models (SSM). For each type of model a separate stream is created on the server which uses a numerical method of the model calculating.

«In Memory Cashed Database» is implemented for information interaction in the training simulator model which allows collecting calculation results in information blocks, and then on demands it allows distributing to customers with the high speed. To store information about the structure of the training simulator model and its parameters SQL Database is used.
2. Development of a simulator model

A simulator model is the OTS core; it is information and software for simulating the behavior of CTS and its hardware environment. The life cycle of the simulator model that is the core of OTS consists of the structural synthesis stages, parametric identification, a calculation scheme construction and a model iterative calculation, integration with the emulation systems of simulated process (operator workstations) and an automated training system. For large-scale projects the effectiveness of the given cycle is determined by the ecosystem of the training complex which includes a set of components for the automated design of the training simulator model, its setup and debugging.

When compiling the mathematical description of CTS in the training simulator model it is necessary to pay special attention to the transition from the general formalism of the description of physicochemical processes to detailed modeling taking into account the specifics of the functioning of real technological devices. In the considered technological objects the LHG storage tank (Figure 2) is the main apparatus. The main feature of this tank is the presence inside it of a heterogeneous system of low-boiling hydrocarbons mixed with an inert gas (nitrogen).

![Figure 3. The LHG storage tank.](image)

In this process the aggregate state of the substance changes and we made following assumptions to take into account such specific processes in the training simulator model:

1. There is a vapor-liquid equilibrium between vapor and liquid.
2. The equations of material and heat balance are described by the ideal displacement model.

As a result the temperature and composition of the vapor and liquid at each point in space are the same. The training simulator model is based on a combination of material and thermal balances and described by the system of algebraic-differential equations below.

The material balance in the liquid phase for the $j$-th component:

$$\frac{dm_{Lj}}{dt} = \sum_i f_{i,j} \cdot F_{Li} - \sum_k x_j \cdot Q_{k,j} - G_j \quad \text{for } j=1,\ldots,n,$$

(1)

where $m_{Lj}$ is the component mass of $j$ in the liquid phase in the tank (kmol); $F_{Li}$ is the total $i$-th fluid consumption into the tank (kmol/s); $Q_{k,j}$ is the total $k$-th fluid consumption from the tank (kmol/s); $G_j$ is the amount of component $j$ evaporating from the liquid (kmol/s); $f_{i,j}$ is the mole fraction of component $j$ in the $i$-th fluid flow entering the tank; $x_j$ is the molar fraction of component $j$ in the fluid flows leaving the tank. The total mass of liquid in the tank $m_L$ is defined as:

$$m_L = \sum_{j=1}^n m_{Lj}.$$

(2)

The molar fraction of component $j$ in the liquid $x_j$ is calculated by the formula:
\[ x_j = \frac{m_{ij}}{m_i} \]  

(3)

The total amount of substance evaporating from liquid \( G \) is calculated by the formula:

\[ G = \sum_{j=1}^{n} G_j. \]  

(4)

The mass balance of vapor occupying the space free from liquid in the tank is calculated by the formula:

\[ \frac{dm_{ij}}{dt} = \sum_r f_{Gr,j} \cdot F_{Gr} - \sum_p y_j \cdot Q_{op} + G_j \text{ for } j = 1, \ldots, n, \]  

(5)

where \( m_{ij} \) is the mass of component \( j \) in the vapor phase (kmol); \( F_{Gr} \) is the total \( r \)-th steam consumption entering the tank (kmol/s); \( Q_{op} \) is the total \( p \)-th steam consumption leaving the tank (kmol/s); \( f_{Gr,j} \) is the mole fraction of component \( j \) in the vapor phase entering the tank by the \( Gr \)-th stream; \( y_j \) is the mole fraction of component \( j \) in the vapor phase leaving the tank.

The volume of steam space is calculated by the formula:

\[ V_G = V - V_L, \]  

(6)

where: \( V \) is the total capacity (m3); \( V_L \) is the volume of liquid in the tank (m3); \( V_G \) is the steam volume in the tank (m3).

The volume of the liquid phase:

\[ V_L = \sum_j m_{ij} \rho_{ij}, \]  

(7)

where \( \rho_{ij} \) is the density of the \( j \)-th component of the liquid in the tank (kg / m3).

Under Dalton’s law, the molar content of each component in the vapor phase is calculated as the ratio between the partial pressure of the component and the total pressure in the vapor phase:

\[ y_j = \frac{P_j}{P_G}, \]  

(8)

where \( P_j \) is the partial pressure of the \( j \)-th component in the vapor phase (Pa); \( P_G \) is the total vapor pressure in the tank (Pa).

The total vapor pressure in the tank is the sum of the partial pressures of the individual components:

\[ P_G = \sum_j P_j. \]  

(9)

The partial vapor pressure satisfies the Mendeleev-Clapeyron equation for real gas:

\[ P_j \cdot V_G = \frac{m_{ij} \cdot R \cdot T}{M_{Gj}}, \]  

(10)

where \( R \) is the universal gas constant \((8.31 \text{ J (molK)}^{-1})\); \( T \) is the temperature in the tank (K); \( M_{Gj} \) is the molecular weight of the gas (kg • kmol\(^{-1}\)).

But the partial pressure of each component is determined under Raul’s law:

\[ P_j = y_j \cdot x_j \cdot P_j^0, \]  

(11)

where \( P_j^0 \) is the saturated vapor pressure above the pure component \( j; \) \( x_j \) is the activity coefficient of the \( j \)-th component [5].
The vapor pressure of pure components depends on temperature and the boiling point $T$ of the mixture and can be approximated, for example, by the Antoine equation:

$$\ln P_j^0 = A_j - \frac{B_j}{T + C_j},$$  \hspace{1cm} (12)

where $A_j, B_j, C_j$ are the constant coefficients.

To determine the temperature the concept of relative volatility $\alpha_j$ is used which is equal to the ratio of the vapor elasticity of the pure $j$-th component $P_j^0$ to the vapor elasticity of the pure reference component or the reference composition of the mixture $P_E^0$ taken at the same temperature:

$$\alpha_j = \frac{P_j^0}{P_E^0}. \hspace{1cm} (13)$$

The temperature is determined [4]:

$$T = \frac{B_E}{A_E \ln(P_G) + \ln(\sum_{k=0}^{m} \alpha_j \gamma_j x_j)} - C_E, \hspace{1cm} (14)$$

and the volatility coefficients of the components presenting in equation (14) are determined from equation [6]:

$$\alpha_j = \exp\left(\frac{B_E}{T + C_E} - A_E - \frac{B_j}{T + C_j} + A_j\right) \hspace{1cm} (15)$$

where $A_E, B_E, C_E$ are the coefficients of the Antoine equation for the reference component.

The heat balance equation from which the component-wise vapor flow is determined, takes into account heat input and output as well as heat consumed or obtained during boiling or condensation respectively:

$$\frac{d\left(T \cdot \sum_j (m_{lj} \cdot c_{lj} + m_{vj} \cdot c_{vj})\right)}{dt} = \Phi - \sum_j G_j \cdot \lambda_j + \sum_i F_{li} \cdot T_{li} \cdot \sum_j f_{li,j} \cdot c_{lj} +$$

$$+ \sum_r F_{gr} \cdot T_{gr} \cdot \sum_j f_{gr,j} \cdot c_{pj} - \sum_k Q_{lk} \cdot T \cdot \sum_j x_j \cdot c_{lj} - \sum_p Q_{lp} \cdot T \cdot \sum_j y_j \cdot c_{pj}, \hspace{1cm} (16)$$

where $\Phi$ is the amount of heat received-given through the surface heat transfer (J/s); $T_{li}$ is the temperature of the $i$-th input fluid flow (K); $T_{gr}$ is the temperature of the $r$-th inlet gas stream (K); $\lambda_j$ is the specific heat of vaporization of the $j$-th component (J/kmol); $c_{lj}, c_{vj}$ and $c_{pj}$ are the specific heat capacities of component $j$ in the liquid and vapor phases at a constant volume and constant pressure respectively (J/kgK)$^{-1}$.

3. Results and Discussion

The conceptual approach represented in this work is successfully being used by the authors as a part of the development of OTS for production facilities for the LHG storage at JSC «Angarsk Polymer Plant» (Irkutsk Region, Russia). Currently in commercial operation there are three OTS designed to provide operations staff with the computer training in storage and transportation of the main liquefied gases in the synthesis of polymers: ethylene, propylene, butylene-butadiene, isopentane, ethyl chloride as well as a wide fraction of light hydrocarbons.
The works' leadership responsibly and systematically fulfils prescribed by federal law the mandatory requirements of equipping hazardous production facilities under their control with the computer training systems. Field experience of OTS allows us to speak with confidence about the positive trends that have been achieved. It is very difficult to assess the direct economic effect of introducing such training systems, but indirect indicators relating to the field of industrial safety are difficult to overestimate.

Firstly, the main point and methodology of training on the OTS is significantly different from traditional approaches to the training and retraining of operations staff which often comes down only to a theoretical study of normative technological documents followed by an exam. Exercises reproduced in the OTS in an interactive situational form allow gaining practical (albeit virtual) experience of events that at the time of training the trainee might not have encountered in real production conditions. This factor significantly develops and strengthens the trainee's associative thinking with a possible hypothetical version of the development of such events on a unit controlled by him.

Secondly, an effective automated aid for self-preparation of newly hired persons appeared at the disposal of the workshops management. The training terms are reduced by several times for personnel who are ready to evaluate and adequately respond to any regular or production contingency.

Thirdly, the use of a built in the OTS automated system for assessing the knowledge of acting production personnel eliminates the possibility of subjective confirmation of its current level of training at the recertification stage that motivates employees to constant self-monitoring and improving their professional skills.

Fourthly, the OTS built-in statistics model allows evaluating and timely responding to potential shortcomings in the employee's mastering components of the industrial safety system of an object by focusing on the «weaknesses» of his preparation.

This list is far from complete and is based solely on the feedback of both the persons themselves involved in the training process at the OTS and the leadership exercising control of their professional level.

In conclusion we would like to note that the role and importance of services providing supervision in the field of industrial safety and labor protection has significantly increased over the past decade in Russia at potentially hazardous production facilities. The main component in this complex production system is a man and his notorious human factor which no technically perfect system can bring to zero. But it is quite possible to minimize it by creating industrial systems of computer training armed with modern information technologies as well as the responsibility and competence of their developers.

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