Chair of Petroleum and Geothermal Energy Recovery

Master's Thesis

# Determination of the amount of oil product vapours from the tank based on monitoring the operation of the breathing valve

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Master Thesis 2022
Petroleum Engineering

# Determination of the amount of oil product vapours from the tank based on monitoring the operation of the breathing valve

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Chair of Petroleum Engineering

*I dedicate this master's thesis to my mother,*

*who has always supported me during my studies.*

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# Abstract

When transporting hydrocarbons from the fields to the consumer, on average up to 5 % of the pumped oil and petroleum products are lost, where up to 90 % of all losses are accounted for by oil depots.

At the moment, there is no automatic system for accounting for vapors of light fractions of hydrocarbons (LFH) from tanks with large and small respiration.

The aim of the scientific work is to develop a new methodology and system for accounting for mass losses of LFH from evaporation from tanks through a breathing valve in real time.

As a result of the work, the hydraulic resistance of the breathing valve was calculated using the Ansys software package. A discrete dependence of the flow rate through the breathing valve was also obtained depending on the degree of opening of the pressure plate and the excess pressure inside the tank. Two cases of pressure plate opening were considered: fully and half. Based on the obtained discrete dependence, formulas $Q(h, \Delta P)$ for calculations were obtained.

With the help of experiments on water and Arduino sensors, it was instrumentally proved that the technique takes place and can be used to calculate LFH losses from the tank.

The equipment for this technique and recommendations on its location were also selected.

# Zusammenfassung

Beim Transport von Kohlenwasserstoffen von den Feldern zum Verbraucher gehen durchschnittlich bis zu 5 % des gepumpten Öls und der Erdölprodukte verloren, wobei bis zu 90 % aller Verluste auf Öldepots entfallen.

Derzeit gibt es kein automatisches System zur Erfassung von Dämpfen leichter Kohlenwasserstofffraktionen aus Tanks mit großer und kleiner Atmung.

Ziel der wissenschaftlichen Arbeit ist es, eine neue Methodik und ein neues System zur Erfassung von Massenverlusten leichter Kohlenwasserstofffraktionen aus der Verdampfung aus Tanks durch ein Atemventil in Echtzeit zu entwickeln.

Als Ergebnis der Arbeiten wurde der hydraulische Widerstand des Atemventils mit dem Softwarepaket Ansys berechnet. Es wurde auch eine diskrete Abhängigkeit der Durchflussrate durch das Atemventil in Abhängigkeit vom Öffnungsgrad der Druckplatte und dem Überdruck im Tank erhalten. Es wurden zwei Fälle von Druckplattenöffnung betrachtet: vollständig und halb. Basierend auf der erhaltenen diskreten Abhängigkeit wurden Formeln $Q(h, \Delta P)$ für Berechnungen erhalten.

Mit Hilfe von Experimenten an Wasser- und Arduino-Sensoren wurde instrumentell nachgewiesen, dass die Technik stattfindet und zur Berechnung von Verlusten aus dem Tank verwendet werden kann.

Die Ausrüstung für diese Technik und Empfehlungen zu ihrem Standort wurden ebenfalls ausgewählt.

# Table of Contents

# Chapter 1

# Introduction

## 1.1 Background and Context

***Relevance of the research topic***. Despite the fact that many studies have been carried out in the oil and gas sector, the problem of accounting for losses from the evaporation of LFH from the tank is still present. Different companies in the country use different methods for accurate calculations. The accuracy of calculations is necessary in order to know the exact residue of the product stored in the tanks, and this will also allow you to accurately know the physico-chemical state of the product, since the composition changes during evaporation.

Evaporation processes from tanks can be of several types. For example, in Russia, losses from evaporation are divided into losses from large and small breaths. In foreign countries, concepts such as "Standing losses" are used, the Russian equivalent of small breaths, that is, as a result of daytime temperature fluctuations, and "Working losses" or losses from large breaths, that is, as a result of emptying and filling.

The evaporation of the O&OP from the tanks leads not only to the deterioration of the physico-chemical properties of the stored product, but also to economic losses, as well as environmental pollution. According to the data of Russian companies, up to 90 % of all losses of non-oil products in the chain from production to consumer use are due to losses from evaporation in the tank. Therefore, accounting for and reducing evaporation losses is an urgent problem in the oil and gas sector.

Therefore, the development of a new method for accounting for losses from evaporation, which will allow more accurately determining the volume of LFH coming out of the tank, is a very urgent problem.

***The degree of development of the topic.*** Domestic and foreign scientists were engaged in the development and development of methods for accounting for losses of O&OP from evaporation: F.F. Abuzova, N.I. Belokon, V.B. Galeev, N.N. Konstantinov, A.A. Korshak, R.E. Levitin, V.I. Chernikin, V.F. Novoselov, J. R. Beckman and others, and also various organizations. The results of the work done have made a significant contribution to the development of methods for accounting for losses from evaporation, which led to the accuracy of their determination. The physical essences of the fumes of the O&OP from the surface of the stored product were described, and various relationships between external factors affecting the tank and the intensity of evaporation were also revealed.

## 1.2 Scope and Objectives

***The scope of the master's research*** is to develop a new methodology and a system for monitoring and accounting for LFH losses from evaporation from tanks in real time.

***Research objectives:***

1. To analyze the available methods of monitoring and accounting for LFH losses from emissions.

2. On the basis of the Ansys software package, build a model of the breathing valve and calculate the flow rate of the gas-air mixture depending on the pressure plate opening rate and the pressure difference (excess and atmospheric), as well as a model of the experimental installation.

3. Conduct experiments using the Ansys software package and Arduino sensors to calculate water losses from evaporation.

## 1.3 Achievements

In the course of the work, the following works were carried out and the following results were obtained:

1. Initially, the CBV 1500/150 breathing valve with a fire barrier was modeled in КОМПАС 3D. To simplify calculations in the Ansys program, the valve was divided into two hydraulic units: a fire starter and the valve itself. As a result, pressure characteristics were obtained for both objects and components, since the losses of the fire barrier compared to the valve are small, they were not taken into account

2. Formulas are obtained for the flow through the breathing valve depending on the degree of opening of the pressure plate and the overpressure $Q$ ($h$, $\Delta P$) for the fully open plate and half.

3. A new methodology and a system for monitoring and accounting for LFH losses from tanks in real time has been developed.

4. An experiment with water was carried out, which shows that the instrumental method can be used in production to calculate LFH losses through a breathing valve in automatic mode.

5. The equipment is selected and recommendations for its installation and use are given.

## 1.4 Technical Issues

In the course of the master's work, a theoretical description of the methodology was carried out, as well as an experiment was conducted to confirm that the methodology is technically feasible. For more accurate results, experiments should be carried out in real conditions, that is, on a real breathing valve and with production equipment. Then it will be possible to judge the exact distortions in the readings between the methodology and the real data.

## 1.5 Overview of Dissertation

The following points were considered in the dissertation:

1. A literature review on this topic has shown that the topic is relevant and currently the accounting of vapors of light fractions of hydrocarbons is not conducted in automatic mode;
2. In the work, a formula was derived for calculating the flow of LFH through the tank's breathing valve, depending on the degree of opening of the pressure cap and excess pressure inside the tank;
3. An experiment was carried out on the water and it was instrumentally proved that the technique can be used to calculate the LFH from the tank;
4. The equipment was selected and recommendations for its installation and use were given.

# Chapter 2

# State of the Art

## 2.1 Empirical methods of accounting for losses from evaporation from the tank

In world practice, as well as in domestic practice, formulas based on empirical data are popular for determining the loss of light hydrocarbon fractions from tanks, and they also use a lot of input data.

In the standard of the American Petroleum Institute (API MPMS 19-1, API MPMS 19-2, 2017), which is used in the "TANK" software to calculate both losses from small breaths and from large breaths.

In this standard, losses are divided into $L_s$ (standing losses) or, as it is customary to count losses due to fluctuations in daytime temperature, small respiration reserves. And also on $L_w$ (working losses) or, as is customary, losses due to pumping and pumping of oil or petroleum products.

The formula for calculating the losses of light fractions of hydrocarbons, adopted by the API and used in the computer program "TANKS", to determine losses with large and small breaths:

$$L_w = NH_{LX}\left(\frac{\pi}{4}D^2\right)\cdot K_N \cdot K_p \cdot K_B \cdot W_V ,[lb / yr] \tag{2.1}$$

$$L_s = 365\cdot V_v \cdot W_V \cdot K_E \cdot K_S ,[lb / yr] \tag{2.2}$$

where $N$ – the rate of turnover of product, rpm/year;

$H_{LX}$ – maximum liquid product level in the tank, ft;

$D$ – inner diameter of the tank, ft;

$K_N$ – loss factor the product of the turnover;

$K_p$ – the loss factor, depending on the type of product;

$K_B$ – the correction factor for the configuration of the breather valve;

$W_V$ – product vapor density, pound/ft$^3$;

$V_V$ – tank vapor space volume, ft$^3$;

$W_V$ – stock vapor density, pound/ft$^3$;

$K_E$ vapor expansion factor;

$K_S$ – vented vapor saturation factor.

Thus, the total losses will be:

$$L_T = L_S + L_W. \quad (2.3)$$

The disadvantages of this method are: the need to know the equipment used on the tank; the design features of the tank; the characteristics of the product in the tank and the most significant drawback - it is necessary to know the coefficients obtained empirically for each region (Zorya E.I., Loshchenkova O.V., 2019).

Another method of accounting for LFH from the tank is presented in document "Control of emissions from tank farms in oil refining sites" (VDI 3479, 2010). This technique is designed for tanks with a fixed roof and also requires a lot of input data about the characteristics of the stored product and the tank. The disadvantage of the proposed technique is that a lot of input data is needed, which is obtained empirically, therefore, the technique is well suited only for regions where all parameters are measured and known.

The following formula is used to determine the losses of LFH from the tank according to the method (VDI 3479, 2010):

$$L_{B,a} = f_B \cdot 12 \cdot 10^{-3} \cdot \frac{1}{T} \cdot p_T \cdot \overline{M} \cdot Q, \quad (2.4)$$

where $f_B$ – degree of saturation;

$T$ – product temperature in the tank, K;

$p_T$ – saturated vapor pressure of the product in the tank at the product temperature, hPa;

$\bar{M}$ – the average molar mass of hydrocarbons in the vapor-air space above the product in the tank, kg/kmol;

$Q$ − amount of liquid poured per year, m$^3$/year.

The disadvantages of the above methods of accounting for LFH include: the lack of accounting for abnormal temperature fluctuations during the day in the area of the tank location, as well as low accuracy of determining LFH.

In Russia, (GD 153-39-019-97, 1997) is used to determine evaporated LFH the following methods are recommended for use: a method for determining oil losses from evaporation by changing the hydrocarbon composition, a method for determining oil losses from evaporation by changing the pressure of saturated vapors.

The first of the mentioned methods used in Russia is based on measuring the concentration of LFH in the gas space of the tank before and after the operation of the breathing valve and further calculations of the released mass.

In addition to the two mentioned methods for accounting for LFH vapors from the tank in GD 153-39-019-97, there are also such methods as: a method for determining oil losses from evaporation by measuring the volume of the vapor-air mixture displaced from the tank, a method for determining oil losses from evaporation by the concentration of hydrocarbon vapors displaced from the tanks, a computational and experimental method for determining losses oil from evaporation from tank parks of fields and trunk oil pipelines.

When using the method of determining LFH losses from evaporation by measuring the volume of a vapor-air mixture, a rotary gas meter is used to measure the outgoing gas-air mixture. To determine the concentration, gas chromatography or gas analyzers KGA 1-1 are used, samples are measured at least 8 times.

The disadvantages of this method are that the concentration of LFCS is determined in the laboratory, which makes the calculation process more difficult, and also a rotary gas meter is determined to determine the flow rate, which is not recommended to use in winter, since the readings may be inaccurate. This method is more designed to account for losses with large breaths, and the error ranges from 6% to 15%.

Summing up, some methods proposed in GD 153-39-019-97 calculate losses very accurately, with minimal errors, but the disadvantages of all methods are that they are not automated and require concentration measurement by laboratory tests, which complicates and lengthens the process.

The patent RU 118621 (Novikov M.V., Novikov K.V., Ovchinin D.I., Stary S.V, 2012) describes a laboratory installation that can be used to compare the accuracy of existing methods of accounting for LFH from the tank. The mass of losses is determined by measuring the difference between an empty electric tank and a filled vapor-air mixture. This installation is suitable for comparing the accuracy of techniques designed to account for the evaporation of LFH during heavy breathing, in laboratory conditions.

The patent SU1121599A1 (Olgin A.E., 1984) describes a method for accounting for LFH vapors from reserves located in oil fields in oil treatment systems. In this method, the mass of evaporated LFH is determined by the mass of the evaporated indicator liquid, which is selected depending on the physical properties of the controlled liquid. The indicator liquid is located in a container in the GS of the tank.

Losses from evaporation are calculated by the formula:

$$G = k \cdot F \cdot \frac{4 \cdot \Delta m \cdot \gamma_M}{\gamma_n \cdot \pi \cdot D^2} \qquad (2.23)$$

where $k$ – the dimensionless evaporation coefficient;

$\Delta m$ – mass of evaporated indicator liquid, kg;

$F$ – the area of the evaporation mirror of the medium under study, $m^2$;

$\gamma_M$ – density of the medium under study, $kg/m^3$;

$D$ – diameter of the evaporation mirror of the indicator liquid, m;

$\gamma_n$ density of the indicator liquid, $kg/m^3$.

The disadvantage of this method is that there is a dimensionless coefficient in the formula, which implies its determination by laboratory studies, and, consequently, the technique is applicable only in regions where studies have been conducted to determine the coefficient. Also, the disadvantage of the method is the location of an additional tank in the tank’s GS with an indicator liquid.

In method (Georgieva A., Koleva D., Panayootova K., Georgiev D., Ivanov Z., 2016) for accounting for the evaporation of hydrocarbons during storage and transportation in railway tanks is considered. The method was developed by the Main Geophysical Observatory A.I.Voeikov. The authors came to the conclusion that with an increase in saturated vapor pressure, emissions increase, which occur mainly due to equipment malfunction, therefore, inspection and maintenance should be carried out more often.

Calculations of losses from evaporation in the method are carried out according to the formula:

$$\Pi = 4,46 \cdot V_T \cdot P_S(38) \cdot M_v \cdot (K_{SC} + K_{SH}) \cdot (K_6 \cdot K_7(1-\eta)) \cdot 10^{-9}, \quad (2.5)$$

where $V_T$ – volume of the liquid in the tank for 1 year, $m^3$/year.;

$M_v$ – molecular weight of vapors of the liquid, g/mol;

$\eta$ – coefficient of efficiency of the tank's gas trap;

$K_{SC}$, $K_{SH}$ – correction factors depending on the saturated vapor pressure and the temperature in the gas space T during hot and cold weather throughout the year;

$K_6$ – correction factor depending on the saturated vapor pressure, determined from reference tables;

$K_7$ – correction factor depending on the technical level and exploitation regime, also determined from reference tables;

$P_S(38)$ – pressure of the saturated vapors of the liquid at temperature of 38°C, GPa.

The disadvantage of this technique is that the formula uses dimensionless coefficients that are calculated for certain conditions, which limits the widespread use of the formula to account for evaporation.

The authors developed a new method (Levitin, R. E.; Tryascin, R. A., 2016) in the laboratory to determine losses during evaporation from the tank. The method is based on the determination of saturated vapor pressure. This method allows you to measure the minimum number of indirect indicators and more accurately determine the number of evaporated LFH. The paper also demonstrates the dependence of evaporation of A92 strongly depends on temperature. The authors of the work concluded that a slight change in the average temperature of 5 degrees Celsius can lead to a 100 % increase in the pressure of saturated vapors. The indirect dependence of the hydrocarbon loss rates on the temperature leads to a distortion of the actual losses of LFH during their storage in the reserve.

The paper («The method of calculation and experimental determination of emissions of pollutants into the atmosphere due to evaporation from storage tanks of petroleum products Krasnodar», 1996) presents a methodology for determining emissions of harmful substances into the atmosphere from a tank during evaporation. The disadvantages of this method are that formulas with experimentally obtained coefficients are used there. Samples are also taken from the tank to measure the pressure and weight concentration of saturated oil vOilapors at the temperature of the gas space. That is an obstacle to automation, acceleration and accuracy of the process.

The calculation of losses from evaporation in the work is carried out according to the formula:

– For tanks with low-boiling products:

$$G_p = V_{ж} \cdot \frac{P_{tr}}{P_a} \cdot \rho_{ntr} \cdot K_n \cdot K_o \cdot 10^{-3} [t / period], \tag{2.6}$$

where $P_{tr}$, $\rho_{ntr}$ – the pressure and density of saturated vapors at the average temperature of the gas space, respectively mmHg and kg/m$^3$;

$V_{ж}$ – volume of petroleum products for the corresponding period of the year passing through a group of single-purpose tanks, m$^3$;

$K_n$ – turnover ratio;

$K_o$ – equipment ratio;

$P_a$ – average barometric pressure, mmHg;

$G_p$ – the amount of losses from evaporation during a period, t/period.

– For tanks with high-boiling products:

$$G_p = V_{ж} \cdot C_{в} \cdot K_n \cdot K_o \cdot 10^{-3} \tag{2.7}$$

where $C_{в}$ the weight concentration of saturated vapors at the average temperature of the gas space, kg/m$^3$.

New criterion equations of mass transfer in vertical steel tanks were obtained (Tugunov P.I., Novoselov V.F., Korshak A.A., etc., 2002), and the influence of various factors on oil losses from evaporation was analyzed. After analyzing the available equations for determining losses, the author comes to the conclusion that they give a large error. Therefore, based on experimental data, the author obtains a new formula for mass transfer.

For the case of stationary oil storage:

$$Kt_{отн} = 3,065 \cdot 10^{-11} \cdot \Delta\pi 0,302 Sc^{3,44} \cdot (\rho_{отн} - 0,7)^{-8,421} \tag{2.8}$$

where $\Delta\pi$ – the modulus of the driving force of the evaporation process;

*Sc* – the Schmidt number;

$\rho_{отн}$ – the relative density of oil at a temperature T = 293 K in the air.

For the case of emptying the tank:

$$Kt_{от} = Kt_{пр}(1{,}104 \cdot 10^6 \Delta\pi^{-0{,}708} \cdot Sc^{2{,}747}\, \mathrm{Re}_{ср}{}^{-1{,}33} + 1), \qquad (2.9)$$

where $\mathrm{Re}_{ср}$ – the average Reynolds number characterizing the rate of washing of the oil surface with air when emptying the tanks.

On the basis of new equations using the methods of (Korshak A.A., Korobkov G.E., Muftakhov E.M., 2006), the values of losses that corresponded to real ones were obtained. The author also argues that the division into autumn-winter and spring-summer periods is not quite adequate, since in autumn and spring the losses are very different from winter and summer, respectively, and therefore methods for determining losses from evaporation should be used differently. There is a corresponding problem with climatic zones. Only 3 climatic zones are considered in the "Standards of natural loss", but even within one zone, the error can be up to 25 % for large breaths and up to 700 % for small breaths.

The paper (Korshak An.A., Korshak A.A., 2018) proposes a method for determining evaporation losses during operation and storage of oil from process tanks. In the proposed method, losses are calculated using various coefficients obtained experimentally. Consequently, these methods can be effectively applied only in regions where the values of the coefficients are known.

Determination of the amount of technological losses of oil from evaporation in technological tanks (t/year):

$$\sum П = \frac{P_{38} \cdot m \cdot (K_t^{\max} \cdot K_p + K_t^{\min}) \cdot K_{тр} \cdot K^{ср}{}_{об} \cdot K_{ссв} \cdot Q_н \cdot 0{,}294}{10^7 \cdot p_н} \qquad (2.10)$$

where $Q_н$ – the amount of oil, tons;

$p_н$ – density of oil, t/m$^3$;

$P_{38}$ – saturated vapor pressure of liquid hydrocarbons at a temperature of 38 °C (mmHg);

$K_{tmin}$, $K_{tmax}$ – experimental coefficients;

$K_{тр}^{ср}$ – experimental coefficient;

$K_{об}$ – turnover ratio;

$K_p$ – the experienced coefficient;

$K_{ссв}$ – the experienced coefficient of efficiency of the means of reducing emissions.

In the document (GD 153-39.4-033-98, 1998), norms for the natural loss of non-oil products at the facilities of trunk petroleum products are proposed. The loss rates are presented in the table, which were obtained experimentally.

In the article (Huang, W.Q., Wang, Z.L., Ji, H., et al., 2016), evaporation losses were numerically modeled and experimentally investigated for various loading volumes. Meanwhile, an experimental system of evaporation losses during loading into the tank was created to test numerical modeling, and the results of numerical modeling are in good agreement with experimental data. The simulation results also showed that the higher the loading yield, the greater the qualitative ratio of the evaporation losses to the loaded gasoline.

The authors recommended taking into account the loading speed and the initial mass fraction of LFH in the formulas for determining evaporation losses developed by the API.

New criteria equations of mass recovery were obtained during operations of emptying (Korshak A. A., Lubin E. A., 2010), filling or idle of the tank, as a result of data obtained from the operation of various tanks. The authors also analyzed the equations obtained earlier, during which the shortcomings were identified, which were eliminated in the developed equations.

As a result of the experiments, the following criteria equations of mass transfer for storage, emptying and filling of tanks were obtained, respectively:

$$Kt_{пр} = 3,065 \cdot 10^{-11} \cdot \Delta\pi^{-0,303} \cdot Sc^{3,44} \cdot \left(\frac{\rho_{293}}{1000} - 0,7\right)^{-8,42} \quad (2.11)$$

$$Kt_{от} = Kt_{пр} \cdot (1 + 1,104 \cdot 10^{7} \cdot \Delta\pi^{-0,708} \cdot Sc^{2,75} \cdot \mathrm{Re}_{ср}^{-1,33}) \quad (2.12)$$

$$Kt_{зак} = Kt_{пр} \cdot (1 + 2 \cdot 10^{6} \cdot \Delta\pi^{-0,45} \cdot Sc^{-2,837} \cdot \left(\frac{\rho_{293}}{1000} - 0,7\right)^{7,249} \cdot (Fr \cdot \mathrm{Re})^{0,188}) \quad (2.13)$$

As a result, the authors conclude that the developed criterion equations have a smaller error than the existing one, which was proved by comparing the calculations and obtaining the standard error.

The advantage of these equations is that they can be used to account for losses from oil evaporation with different properties, in tanks with different amounts, and also that calculations are carried out according to the initial concentration of carbohydrates, which helps to avoid multiple iterations contained in the old calculations.

Two methods were developed (Bahadori, A.; Baghban, A.; Bahadori, M.; Kashiwao, T.; Ayouri, M. Vafaee, 2016) to account for evaporation losses based on the support vector machine (SVM) and adaptive network based fuzzy inference system (ANFIS). Two models were trained on the basis of data obtained from the experience of tank operation in the past.

During the experiments, based on statistical analysis, the SVM-based program showed greater accuracy in determining evaporation losses than ANFIS. The proposed models are easy to use and will be able to assist in the design of storage tanks. The use of a software package will help engineers and researchers to better control the operating conditions of the tank.

The new technique (Bahadori, Alireza; Vuthaluru, Hari B., 2010) was developed for determining losses from vapors during tank filling based on experimental data. The tank filling losses are estimated as a percentage of the injected liquid depending on the operating pressure and the pressure of the gas-air mixture at the temperature of the injected product.

The authors conclude that the method is consistent with the data available in the literature, so the average deviation of the data obtained by the method and real data is less than 2 %.

The document (Kazan, 1999) presents methodological guidelines for determining emissions of pollutants into the atmosphere from the tank, developed in the city of Kazan. The document presents calculation methods for the emission of vapors of oils, gasoline and petroleum products (except gasoline).

Formula for determining oil and gasoline vapor emissions:

$$G = \frac{P_{38} \cdot m \cdot (K_t^{\max} \cdot K_в + K_t^{\min}) \cdot K_p^{ср} \cdot K_{об} \cdot B \cdot 0,294}{10^7 \cdot \rho_{ж}} [t / year] \tag{2.14}$$

where $P_{38}$ – the pressure of saturated vapors of liquid hydrocarbons at a temperature of 38 ° C;

$K_{tmin}$, $K_{tmax}$ – the experienced coefficients;

$K_p^{cp}$ – the experimental coefficient;

$m$ – molecular weight of liquid vapor;

$K_в$ – experimental coefficient;

$K_{об}$ – turnover ratio;

$\rho_{ж}$ – liquid density, t/m$^3$;

$B$ – the amount of liquid pumped into the tank during the year, t/year.

The document also presents an instrumental method for determining the emissions of pollutants. To determine the concentration of LFH, a gas chromatographic method is used, that is, a sample is taken from the tank and the concentration of LFH in the GS of the tank is determined in laboratory conditions, and the concentration of hydrogen sulfide is determined by photometric method.

The disadvantages of the presented methods are such factors as: the use of coefficients that were obtained for certain conditions, the lack of automation in the case of calculating losses in the concentration of hydrocarbons in the tank's GS.

In the dissertation (Kulagin A.V., 2003), an improved method of gasoline losses from underground gas station tanks was presented, in which new criterion equations of mass transfer were obtained based on the experimental data obtained. Subsequently, a methodology was developed for determining the losses of gasoline from the gas station THS AFS.

In comparison with previously developed methods, the proposed method takes into account the turbulence of the liquid when filling the tank. The standard error of losses from large breaths calculated by this method and the experimental data obtained is 18.9 %.

The new method was developed and patented (Molchanov O.V., Navmatullin A.Z., Khudynin S.V., Dmitriev S.V., Kabanov V.I., 2002) to determine the losses from the evaporation of LFH from the tank during small and large breaths.

The flow rate of the gas-air mixture is determined by the specified aerodynamic resistance of the breathing valve, control of the entire range of the lifting height of the valve stem and the pressure of the gas-air mixture, thereby increasing the accuracy of measurements.

The essence of the technique is that, depending on the lifting of the pressure plate, the aerodynamic resistance of the breathing valve also changes, and, consequently, the flow rate through it. The aerodynamic resistance of the breathing valve is determined experimentally. The pressure drop, the height of the plate lifting and the concentration of the outgoing LFH are determined using instruments.

The data obtained for calculating the amount of losses from evaporation are substituted into the formula:

$$Q = \frac{\pi D h}{\sqrt{1+\xi}} \sqrt{\frac{2\Delta P}{\rho}} \qquad (2.15)$$

where ρ – the average density of the vapor-air mixture;

ζ – aerodynamic resistance of the breathing valve.

According to the description of the technique, it is not clear where and how the devices will be installed inside the tank.

The disadvantage of the methods obtained empirically is that they are mostly suitable, that is, they adequately calculate the losses of LFH from evaporation in tanks, only for those conditions and cases in which they were obtained. This means that the widespread use of these techniques will lead to significant errors.

## 2.2 Theoretical methods of accounting for losses from evaporation from the tank

The Russian patent RU 2561660 (Zemenkov Yu.D., Levitin R.E., Dyakov K.V., 2014) presents a method for determining the losses of oil and petroleum products from evaporation during small tank breaths by measuring the excess pressure in the tank, atmospheric pressure, and measuring the average temperature of the gas space of the tank. As stated by the authors and calculations are given as an example, the formula provides an increase in accuracy.

The essence of the technique is that initially the concentration of hydrocarbons in the tank's GS is measured using laboratory tests, using gas chromatographic analysis. Such a test is carried out when the tank is put into operation. Next, the concentration will be calculated from the formulas.

When registering excess pressure and adjusted for temperature, the change in the concentration of LFH in the GS of the tank is calculated according to the formula:

$$\Delta c = \frac{M \cdot 273}{22,4 \cdot 101325} \left( \frac{P_2 + \Delta P_{атм}}{T_2} - \frac{P_1}{T_1} \right), \left[ \frac{kg}{m^3} \right] \qquad (2.16)$$

where $P_1$, $P_2$ – the value of the absolute pressure in the tank, Pa;

$T_1$, $T_2$ – average values of the temperature of the gas space of the tank, K;

$\Delta P_{атм}$ – increase in atmospheric pressure, Pa;

$M$ – molar mass of oil or petroleum product vapors, g/mol.

If the overpressure is less than the lower threshold of the breathing valve actuation for vacuum, then the change in mass concentration is determined by the formula:

$$\Delta c = \frac{M \cdot 273}{22,4 \cdot 101325}\left(\frac{P_2 + \Delta P_{атм}}{T_2} - \frac{P_1}{T_1} - \sum_{i=1}^{n} \frac{\Delta P_{bi}}{T_{bi}}\right), \left[\frac{kg}{m^3}\right] \qquad (2.17)$$

where $n$ – the number of actuations of the breathing valve to vacuum;

$\Delta P_{bi}$ – pressure increase during the i-actuation of the breathing valve on the vacuum, Pa;

$T_{bi}$ – the average value of the temperature of the gas tank during the operation of the exhaust valve for vacuum, K.

After that, knowing the change in mass concentration, it is possible to calculate the mass losses that occurred during the operation of the breathing valve., according to the formula:

$$m = c\left(\frac{P_1 V T_2}{P_2 T_1} - V\right), [kg] \qquad (2.18)$$

where $P_1$, $P_2$ – the value of the absolute pressure in the tank before and after the operation of the exhaust valve, Pa;

$T_1$, $T_2$ – the values of the temperature of the gas space of the tank before and after the operation of the breathing valve, K;

$V$ – the volume of the gas space of the tank, m$^3$;

$c$ – the concentration of hydrocarbons in the gas space at the time of opening the breathing valve.

$$c = c' + \Delta c, [\frac{kg}{m^3}] \qquad (2.19)$$

where $c'$ – the initial concentration of LFH in the gas space of the tank, kg/m$^3$.

If the tank was only put into operation after construction or reconstruction, the tank should be fully ventilated, and then the initial concentration regulation will be equal to 0. In other cases, it must be measured before the system is put into operation, for example, by means of a gas chromatographic study.

Then the total mass losses are determined:

$$M = \sum_{i=1}^{n} m_{i,} [kg] \tag{2.20}$$

A similar method was developed and described in patent RU 2541695 (Buzenkov O.P., Kabanov V.I., Mironov N.A., Molchanov O.V., Novikov M.V., 2013). The uniqueness of this method from the previous one is that in addition to the vapors of LFH from small exhalations, it is also possible to calculate losses with large breaths using the following formulas:

$$V_n = V_{ГП} \cdot \frac{C_{0M} R_0 T_0}{P_a M_П} \cdot \left[ \frac{C_{1M} T_1 \left( P_a M_П - C_{0M} R_0 T_0 \right)}{C_{0M} T_0 \left( P_a M_П - C_{1M} R_1 T_1 \right)} - 1 \right] \tag{2.21}$$

or

$$V_n = V_{ГП} C_{0П} \left[ \frac{C_{1H} (1 - C_{1П})}{C_{1П} (1 - C_{1H})} - 1 \right] \tag{2.22}$$

where $V_{ГП}$ – the volume of the gas space of the tank, m$^3$;

$C_{0M}$, $C_{1M}$, – mass concentration of hydrocarbons in vapors before and after respiration, kg/m$^3$;

$C_{0П}$, $C_{1П}$ – volume concentration of hydrocarbons in vapors before and after respiration, volume fractions;

$R_о$ – the universal gas constant, J/(mol·K);

$M_n$ – molecular weight of hydrocarbon vapors, kg/mol;

$P_a$ – atmospheric pressure, kPa;

$T_0$, $T_1$ – the temperature of hydrocarbon vapors before and after respiration, K.

The method (Abuzova F. F., Bronstein I. S., Novoselov V. F., 1981) is new, since no additional losses associated with the evaporation of LFH during the filling of the tank and the change in the thermodynamic state of the gas mixture have been taken into account anywhere before.

Usually, in previous methods, losses with large breaths were equated to the volume of the injected product ($V_{БД}$=$V_{ЗАК}$).

The volume of the gas space is measured in accordance with GOST 8.595-2004, the average temperature values are measured in the middle of the gas-air mixture before and after respiration, the concentration values are also measured before and after respiration by taking samples and conducting gas chromatography in laboratory conditions. The accuracy of the method depends on the number of samples taken.

In (Littlejohn, David; Lucas, Donald, 2003), a new technique was considered for accounting for the evaporation of LFH from tanks storing heavy oil as a result of space ventilation. Prior to this, it was not proposed anywhere to take into account these losses of LFH from heavy oil. The method uses a device for ventilation of the tank's GS with subsequent registration of the concentration of oxygen or other gases contained. New losses, taken into account in the proposed methodology, arise as a result of the release of gases from oil and are removed from the tank through ventilation holes in the tank. According to the authors, this method allows you to take into account all the losses from the tank in full.

There is a known method for determining losses from the evaporation of LFH with small breaths, which is described in (Georgieva A., Koleva D., Panayootova K., Georgiev D., Ivanov Z., 2016). To calculate the losses, the formula is used:

$$V = V_{ГП} \ln\left(\frac{P_A - P_{КВ}}{P_A + P_{КД}} \cdot \frac{100 - C_{\min}}{100 - C_{\max}} \cdot \frac{T_{П\max}}{T_{П\min}}\right) \tag{2.24}$$

where $V_{ГП}$ – the volume of the gas space (GS) of the tank, m$^3$;

$C_{min}$, $C_{max}$ – minimum and maximum volume concentration of hydrocarbon vapors in the tank's GS during the day, %;

$T_{Пmin}$, $T_{Пmax}$ – minimum and maximum temperatures of the GP tank during the day, K;

$P_{КВ}$, $P_{КД}$ – pressure of actuation of the breathing valve of the tank for vacuum and overpressure, Pa;

$P_A$ – atmospheric pressure, Pa.

The disadvantages of this method are: applicability only for the determination of hydrocarbon losses at low breaths, the difficulty of determining the minimum and maximum concentrations of hydrocarbon vapors contained in the tank's GS, a large error due to the determination of the temperatures of the gas space of the tank.

The article (Kuznetsov E.V., 2010) provides a methodology for predicting hydrocarbon losses during evaporation from tanks, and the calculation procedure was also given. This model describes the process of large, small and reverse respiration, taking into account the relationship between the processes of heat and mass transfer, the parameters of technological modes and the influence of the surrounding environment. The Holt method, modified in the work, is used to predict the losses of petroleum products. Also in the work, a methodology has been developed to reduce losses with the help of which it is possible to see potentially dangerous places in oil fields for oil and petroleum product losses. The disadvantage of this technique is the use of a large amount of input data and the use of correction coefficients, which can lead to inaccuracy of calculations.

A methodology for accounting for oil evaporation from the tank was developed by (Smolentsev V.M., 2003). In the course of the work, experiments were carried out, as a result of which a new equation was obtained for calculating the intensity of oil evaporation in the tank in the presence of pumping, and a formula was obtained for calculating the mass of evaporated oil under dynamic conditions, the formulas use a new criterion obtained during experiments.

$$G = G_0(1,0 - 0,00605 K_{SA}{}^{0,584})\left[P_{S0}\left(1 + 1,54 \cdot 10^{-6} K_{SA}{}^{1,77}\right) - P\right] \tag{2.25}$$

where $G_0$ – the mass flow rate of evaporating oil during storage, kg/s;

*Pso* – saturated vapor pressure during oil storage under specified conditions;

*P* – partial pressure of oil vapors in the gas space.

It is revealed that in the processes of mass transfer during static and dynamic evaporation of oil in the tank, the determining parameters of the evaporation intensity are the diffusion time and the time of filling the tank. A technique has been developed that predicts oil losses during evaporation from tanks connected to the main pipeline as a result of different oil pumping modes. At the heart of the development, the formula of F.F. Abuzova was used to determine the concentration of the vapor-air mixture.

The paper (EPA-450/4-88-004, October 1988) presents methods for accounting for the evaporation of LFH from different types of tanks for large and small breaths, developed by Environmental Protection Agency. The methods are similar to those presented in (API Chapter 19.4), but in this paper the equations are refined and improved. The disadvantages of the methods developed by the EPA are that their calculations use coefficients that have been experimentally obtained for certain conditions, that is, the formulas will give a large error if they are considered in unexplored regions, which makes the formulas not universal.

In the candidate's work (Bazhenov V.V., 2007), errors in previous developments on the accounting of vapors from the tank were analyzed and a mathematical model of the entry into the atmosphere of the gas-air mixture coming out of the tank was developed, which further allowed the development of software that controls the pollution of the atmosphere from the tank, that is, the accounting of vapors. The improved method takes into account weather changes, physico-chemical properties, stored product, design and technical equipment of the tank. The developed system allows monitoring emissions into the surrounding atmosphere in real time.

The emission of petroleum product vapors is determined by the formula:

$$g = \frac{\left(\frac{k_2}{k_1} \cdot 10^{-3} \frac{D_n S C_в}{h} \ln \frac{P}{P - P_{ж}}\right)}{3600} \tag{2.26}$$

where $g$ – the emission of petroleum product vapors, g/s;

$k_1$ – correction factor, taking into account the decrease in the temperature of the evaporation surface;

$k_2$ – a coefficient that takes into account the reduction of evaporation due to the overlap of the surface with a pontoon,

$S$ – total evaporation surface area, m$^2$;

$C_в$ – concentration of oil product vapors in the gas-air space, mg/m$^3$;

$h$ – oil product rise, m;

$P_ж$ – partial vapor pressure of petroleum product, millimeters of mercury.

Based on a comparative analysis of the improved method and the available methods for calculating vapors from the tank, the author concludes that the final result has the same order, but the proposed method takes into account fluctuations in second emissions of harmful substances, while the existing method determines the second emission as the maximum possible for the entire calculation period.

The disadvantage of the technique is the calculation of the concentration of LFH in the gas-air mixture coming out of the tank occurs according to the (OND-86, 1986) method, in which the formula for calculation is used, where there are many correction coefficients, which can lead to an error in calculations, and also makes the system suitable for operation in conditions where coefficients were measured.

In the dissertation (Levin M.Y., 2021), a new mathematical model was developed for describing the phenomena of heat and mass transfer during fuel storage and modeling convection movements as a result of uneven heating of the tank. The influence of solar radiation on the amount of evaporating LFH is considered. As a result, a mathematical model was obtained, with the help of which it is possible to calculate losses from a horizontal cylindrical tank with greater accuracy and obtain values close to reality, thereby increasing the efficiency of loss accounting. Based on a mathematical model, a neural network was developed to evaluate the operational parameters of a horizontal tank, including losses during evaporation of LFH.

A method was developed for predicting the total losses of O&OP from large breaths over a long period (Korshak An.A., Korshak A.A., 2018). In the previously used methods, the turnover coefficient of the tank was incorrectly calculated, therefore, the losses of LFH from evaporation from the tank during large breaths were underestimated by calculation than it actually was. Therefore, the authors of the work have developed a new secondary coefficient to determine the losses from evaporation during large breaths when pumping the O&OP "through the tank" for a given long period. The authors concluded that when determining losses with large breaths, it is necessary to look at the actual operation scheme of the tank, as well as use their correction factor for more accurate calculations.

The paper (Alekseev T. S., 1955) presents a method for accounting for the evaporation of petroleum products from the tank. The proposed method is derived from the fundamentals of the theory of thermal calculations of gasoline storage facilities, developed by N.I. Belokon, with amendments. Thus, the proposed methodology uses coefficients obtained on the basis of experiments, which a priori carries an error in calculations.

In paper (Weiqiu H., Jie F., Fei L., Hong J., Hongning W., 2019) an experiment was carried out in a wind tunnel using a floating roof resonator model and on the basis of the experiments conducted and the theory of mass transfer from the film surface, the dependence of the film thickness and evaporation rate was proposed and numerically verified. The air flow velocity, the concentration of LFH during evaporation and the rate of losses during evaporation from the tank were calculated using a model. Factors such as the location of ventilation openings, the height of the gaps between the floating roof and the tank, and how they affect the rate of evaporation of oil from the tank were also analyzed.

The results additionally show the internal mechanism of mass transfer, which may be useful in the future when designing tanks with a floating roof. It was also deduced that when the floating roof rises, evaporation losses increase, as the wind speed increases on the roof top, and when the roof is at the same level, evaporation losses decrease. Ventilation openings are better placed on the roof than on the wall. To reduce losses, the O-rings must be improved.

The article (Ginestet, S.; Le Bot, C., 2018) considers the effect of fire near the tank on the amount of evaporation from it. A numerical approach has been developed to determine the volume of escaping vapors, based on the thermodynamic hypothesis, a simplified method for estimating the amount of LFH escaping from the tank during evaporation has been proposed. Also, later, an algorithm was proposed for how temperature, pressure and flow rate change over time, which is valuable information for further research, as well as safe operation.

A new developed method for calculating losses from evaporation from a tank is presented in (Huang, W., Bai, J., Zhao, S., & Lv, A., 2011). A comparative analysis of emissions calculated using three different methods was carried out: an empirical method developed by the API; a theoretical method developed by the authors of this article, and an experimental method presented in (Okamoto, K., Watanabe, N., Hagimoto, Y., Miwa, K., & Ohtani, H., 2009). In the methodology presented by the authors, losses from evaporation are calculated by calculating the concentration of LFH in the outgoing stream.

The authors of the developed theoretical method come to the conclusion that this technique, integrated into the PELES-2.0 software, designed to calculate evaporation losses, can be used for accurate calculations of LFH vapors from the tank, and can also provide basic recommendations to both managers of enterprises and developers of devices that control emissions.

In paper (Rota, Renato; Frattini, Simone; Astori, Sabrina; Paludetto, Renato, 2001), a mathematical model was developed to determine the loss from the evaporation of LFH in the storage tank, and an analysis was also carried out with semi-empirical ratios obtained by other scientists and with experimental data obtained in real conditions.

According to the results of the study, the authors of the article concluded that the LFH inside the tank are stratified, and, consequently, diffusion plays a key role. Also, in an experiment conducted on a real tank, concentrations below the saturation level were recorded in the outgoing flow of LFH.

The developed mathematical model can be used to calculate losses for large and small breaths with greater accuracy than using the methodology proposed by the API. The model showed slight deviations of the values obtained by laboratory means.

In paper (Beckman, James R.; Gilmer, James R., 1981) James R. Beckman developed a mathematical model for predicting the amount of oil losses from evaporation occurring in the tank. The model with an accuracy of up to 10 % predicted emissions from the tank as a result of evaporation, which was very accurate, in comparison with the empirical methods proposed by the API, which gave an error in calculating losses as a result of tank respiration 100 % more than the available real evaporation.

The authors also concluded that the gas-air mixture inside the reserve is stratified and does not mix, and that the upper part plays the greatest role in determining evaporation losses, as well as that diffusion plays a significant role in calculations.

In his next work (Beckman, James R., 1984), James R. Beckman developed a diffusion model of simultaneous heat and mass transfer, which predicted the loss of LFH from evaporation in the tank as a result of respiration. The model was divided into external and internal environments.

The internal model of the tank used parametric excitation methods to solve coupled transport partial differential equations. A simplified external model of the tank estimated the temperature of the upper dome of the tank taking into account the emissivity of the dome, solar insolation, the influence of ambient air temperature, wind speed and the heat capacity of the dome metal.

The comparative analysis of the developed methodology with the WOGA program was satisfactory, but a more detailed consideration of the problem is required.

In article (Beckman, James R.; Holcomb, Jeffrey A., 1986), James R. Beckman, together with Jeffrey A. Holcomb, presented a diffuse model of the final state, which predicted losses from vapors during large breaths of a tank with a fixed roof.

This model was tested and confirmed by experiments conducted in laboratory conditions on a model of a reduced tank. It was suggested that this model would be used as an extension to the API methodology. The model is suitable for calculating losses from evaporation of both oil and petroleum products.

Theoretically, the methods obtained can already be integrated much better into other terrain conditions for calculating the losses of O&OP from evaporation from tanks. The disadvantage of these techniques can only be that a large amount of input data is required for their application, which can complicate the calculation.

## 2.3 Analysis of available techniques

he analysis of the available methods will allow to take into account the shortcomings in the previously developed methods obtained empirically or theoretically, and thereby eliminate or minimize errors, which will lead to a more accurate determination of the losses of O&OP from evaporation from tanks.

In paper (Zorya E.I., Loshchenkova O.V., 2019), a comparative analysis of the methods (API Chapter 19.4, 2017; VDI 3479, 2010; RU2561660C1, 2014; Konstantinov N.N., 1961) was carried out to account for losses from evaporation as a result of small tank respiration.

In general, the methods under consideration interpret the process of LFH evaporation from the surface of the stored product in the same way. The differences are only in the initial data, the degree of elaboration and the accuracy of the definition.

The disadvantages of the methods developed by Russian scientists are that they require a lot of input data, are not adapted to production conditions and do not have the status of official regulatory documents, and not all formulas are correct.

Regarding the American methodology, it could be the most preferable of all compared, in terms of the degree of detail and accuracy. But the methodology uses coefficients that are specific only to the conditions of the United States, which is a limiting factor for use everywhere.

In paper (Elizaryev, Alexey; Tarakanov, Dmitry; Aksenov, Sergey; Tarakanov, Denis; Elizareva, Elena; Nasyrova, Elina; Nazyrov, Airat, 2020), a comparative analysis of the methods presented in (API Chapter 19.4, 2017; VDI 3479, 2010) and the methodology developed by Tugunov P.I. and Novoselov V.F. "Model calculations for the design and operation of tank farms and oil pipelines" was carried out (Abuzova F. F., Bronstein I. S., Novoselov V. F., 1981).

The formula for calculating filling losses developed by the above-mentioned scientists:

$$G_{sb} = \left[ V_H - V_{gs} \cdot \left( \frac{P_2 - P_1}{P_2 - P_{ypump}} \right) \right] \cdot \frac{P_{ypump}}{P_2} \cdot \rho_y, [kg] \tag{2.27}$$

where $V_H$ – volume of oil injected into the tank, m$^3$;

$V_{gs}$ – the volume of the gas space in front of the oil pumping, m$^3$;

$P_2$ – absolute pressure in the gas space at the end of the injection, Pa;

$P_1$ – absolute pressure in the gas space at the beginning of injection, Pa;

$P_{ypump}$ – the estimated average partial pressure of oil vapor in the process of filling the tank, Pa;

$\rho_y$ – the density of oil vapor, kg/m$^3$.

As a result, the authors came to the conclusion that the most accurate method of the three compared was the method developed by Russian scientists Tugunov P.I. and Novoselov V.F., since in this method the maximum and minimum temperature per day was taken into account in the input data, which turned out to be a key factor. In the works (API Chapter 19.4, 2017; VDI 3479, 2010), the error reached up to 30 %.

In paper (Maksimenko A.F., Dyachenko I.F., Lopovok S.S., 2016), a comparative analysis of several techniques was carried out (Korshak S.A., 2003; Mukhamedyarova R.A., Abuzova F.F., 1981), where the analysis of factors affecting the final result of calculating evaporation losses with large breaths was carried out.

The authors came to the conclusion that the equations presented in (Mukhamedyarova R.A., Abuzova F.F., 1981) do not correspond to reality, since they show that LFH practically do not age in the interoperative period, although in reality this is not the case, and according to the equations from (Korshak S.A., 2003) it is obtained that the concentration of LFH increases at tank emptying operations, which also does not correspond to experimental data.

Based on the data obtained as a result of the experiment, the authors of the article (Maksimenko A.F., Dyachenko I.F., Lopovok S.S., 2016) obtained new equations for calculating the losses of LFH vapors from the reserve during large breaths.

The authors of the article claim that the use of techniques (Korshak S.A., 2003; Mukhamedyarova R.A., Abuzova F.F., 1981) to determine the losses of LFH can lead to significant deviations from the actual values. In their methodology, the authors used the values of the average monthly temperature, that is, they used tabular values, and the concentration value at the beginning of emptying was 90 % of the saturation concentration values, which is a disadvantage in the methodology, since it can lead to inaccuracies in calculations.

In the article (Maksimenko A.F., Lopovok S.S., 2015), a comparative analysis was carried out between the methods for calculating LFH emissions from the tank. The methodology of the Ministry of Energy of the Russian Federation and the methodology proposed in the USPTU are considered. The authors concluded that according to the methodology proposed in the USPTU, the data are obtained more accurately than according to the methodology from the Ministry of Energy of the Russian Federation. In the methodology, it is proposed to calculate large breaths according to the formula of V.I. Chernikin, and small ones according to the formula of N.N. Konstantinov. An addition to the developments at USPTU was that new criterion equations of mass transfer were obtained with the help of which the concentration at the end of the process is calculated.

The method differs from the previous one in that the criteria equations use slightly different values of degrees that were obtained as a result of experimental data, which once again confirms that the formulas obtained experimentally may differ for different cases.

The paper (Mednikova, M. I. (Ed.), 2017) presents a comparative analysis of several techniques, and specifically losses during evaporation from the tank as a result of large breaths, developed by Russian scientists (Korshak A.A., Korobkov G.E., Muftakhov E.M., 2006; Abuzova F.F., 1977; Tugunov P.I., Novoselov V.F., Korshak A.A., etc., 2002). The analysis of the formulas for accuracy was carried out using the VST-20000 tank, on which the input data during oil injection were measured. As a result, the authors of the works come to the conclusion that the most accurate method of the above is the method developed by A.A. Korshak (Korshak A.A., Korobkov G.E., Muftakhov E.M., 2006), since it is the most theoretically justified, the geometric dimensions of the tank and the saturation of the GS of the tank as a result of pumping are taken into account.

# Chapter 3

## Development of a method for determining the amount of oil product evaporation from the tank

### 3.1 Simulation of the flow through the breathing valve in the Ansys software package

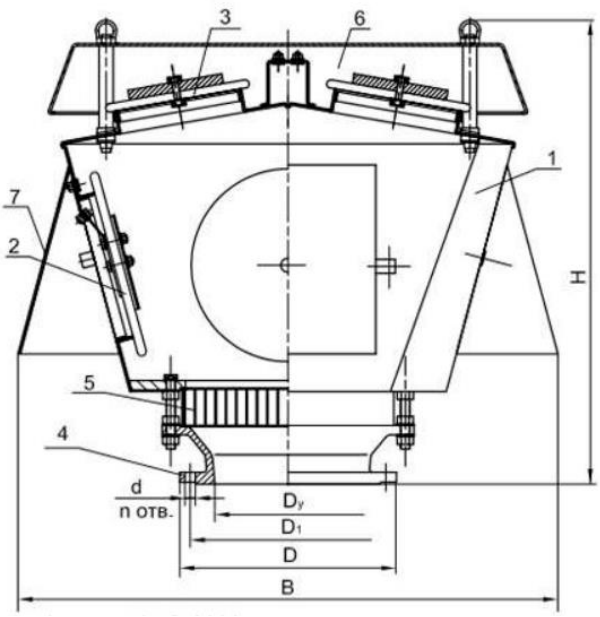
To implement the conceived method, it is required to analyze the dependence of the flow rate from the valve based on the ratio of the degree of opening of the valve pressure plate and the pressure difference (overpressure in the tank and atmospheric pressure outside).

In the Ansys program, to determine the ratio of the height of lifting the pressure plate and flow rate, a combined CBV-1500 exhaust valve was selected as an experimental object (Figure 3.1). The valve characteristics are presented in Table 3.1.

*Table 3.1 Characteristics of the CBV-1500 breathing valve*

| Name of the parameter | Breath valve CBV-1500 |
|---|---|
| Conditional passage, mm | 150 |
| Working pressure, Pa (mm of water) | 2000 (200) |
| Working vacuum, Pa (mm. of water) | 250 (25) |

| Name of the parameter | | Breath valve CBV-1500 |
|---|---|---|
| Actuation pressure, Pa (mm. of water) | | 1500-1600 (150-160) |
| Actuation vacuum, Pa (mm. of water) | | 100-150 (10-15) |
| Throughput capacity, $m^3/h$ | | 450 |
| Overall dimensions, no more: | | |
| length, mm | | 900 |
| width, mm | | 900 |
| height, mm | | 800 |
| Cross-sectional area of pressure plates, $cm^2$ | | 940 |
| Cross-sectional area of vacuum plates, $cm^2$ | | 1900 |
| Connecting dimensions | D | 260 |
| | D1 | 225 |
| | d | 18 |
| | n, pcs. | 8 |
| Weight, kg, no more | | 85 |




1 – housing; 2 – vacuum plate; 3 – pressure plate; 4 – adapter; 5 fire fuse; 6 – cover; 7 – visor.

*Figure 3.1 Schematic representation of the combined breathing valve*

.And in Figure 3.2, you can see the designed valve looks like a 3D Compass, in which there is a fire barrier.

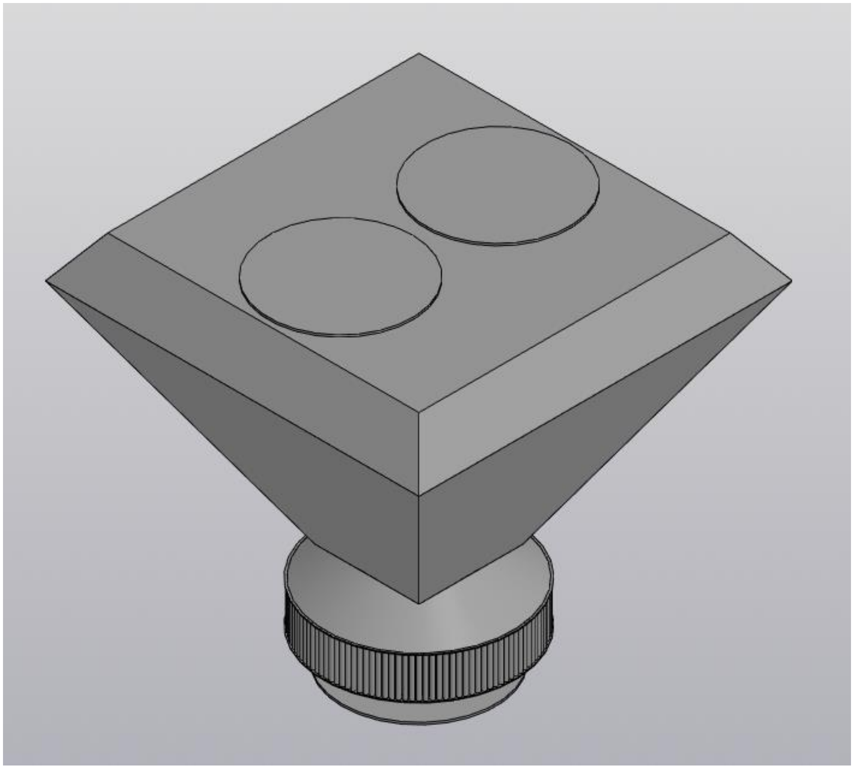
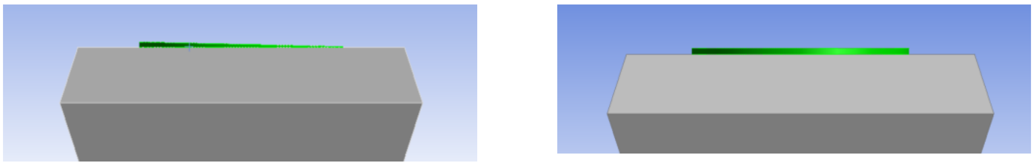


*Figure 3.2 Breathing valves in КОМПАС 3D with a fire barrier*

The principle of operation of the valve is simple. When the pressure in the tank increases to a critical level, two pressure seats located on the upper part of the valve open and the excess pressure resulting from the formation of gaseous carbons decreases. If a vacuum occurs in the tank, the vacuum containers located on the sides of the valve open and the air mass enters the tank from the atmosphere. The fluoroplastic film contributes to the freezing of the contacting surfaces.

The valve was designed in Ansys starting from the connecting element, that is, starting from the adapter that is attached to the tank roof, and the valve was designed only to simulate the overpressure outlet, plates triggered by vacuum were not designed and the model of air entry into the tank was not considered.

During the calculation of expenses through the breathing valve, it was decided to make two tables: one for a fully open plate, the other for a plate half open. This calculation will help to take into account all situations, even if the plate cannot function normally (Figure 3.3). Initially, it was decided to make calculations for a simplified valve model, that is, with one pressure plate and without a fire barrier. Thus, Figure 3.2 shows a combined breathing valve with a maximum throughput of 450 $m^3$/hour and an inlet (inlet) diameter of 150 (CBV-1500/150).



a) half b) completely

*Figure 3.3 Methods of opening the pressure plate in the breathing valve*

Since, from the point of view of grid construction, it is difficult to count a breathing valve with a fire barrier in Ansys, it was decided to divide the valve into two components and calculate their costs and pressures separately, that is, for a breathing valve without a fire barrier Figure 3.5 and for a fire barrier, which are located sequentially, and therefore, the pressure characteristics are simply stored to get the total.

In the CBV-1500/150 fire barrier, 886 identical elements turned out, therefore, in order to calculate the pressure characteristic of all, it is enough to get losses for one element of the fire barrier and divide by the total number, since the elements are located in parallel. Figure 3.4 shows one element of the exhaust gas barrier with a diameter of 10 mm and channels of 2 mm are located inside it.

In order to understand how much the fire barrier affects the flow rate through the breathing valve, calculations of losses were carried out depending on the flow rate through the fire barrier. Expenses were taken through the breathing valve when the pressure plate was raised by 10 mm, since in the Ansys program the calculation for the fire barrier is made for one branch pipe, then the expenses were divided by 886, there are only 886 branch pipes, and with a parallel arrangement, the flow is divided equally.

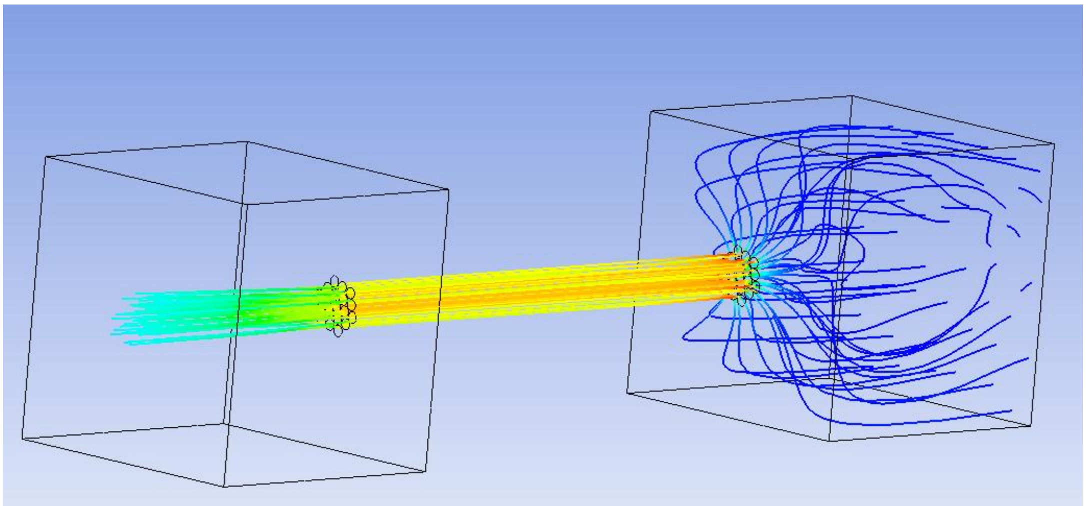


*Figure 3.4 The drawing of one link of the fire barrier*

As a result, we obtained two graphs of dependencies $H(Q)$ for the fire barrier, from above, and for the breathing valve, from below (Figure 3.5).

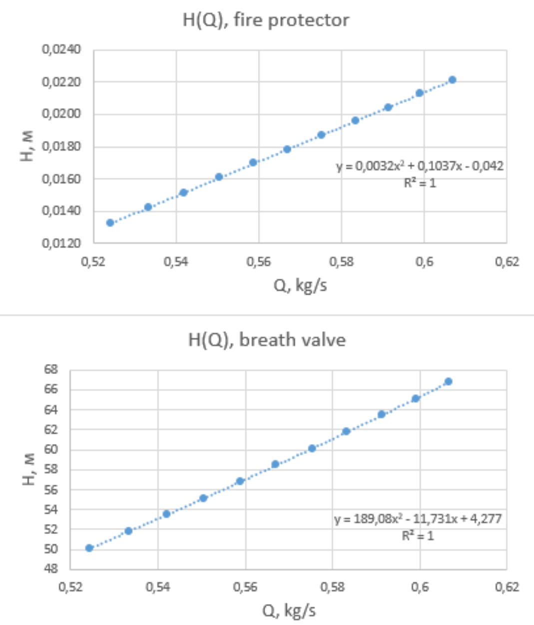



*Figure 3.5 The pressure characteristic H(Q) for the fire barrier and for breathing valve*

As can be seen from the graphs, with the same expenses, the losses on the fire barriers are very small compared to the losses on the breathing valve, so the influence of the fire barrier on the consumption was not taken into account further.

As a result of the calculations in the Ansys program, two tables were obtained in which the flow rate of the vapor-air mixture through the pressure plate is presented, depending on the degree of opening of the pressure plate and the pressure difference (Appendix A, B).

Knowing the degree of opening of the pressure plate and the pressure difference, it will be possible to determine the flow rate of the gas-air mixture through the breathing valve of the tank in the result of large and small breaths. The model of the exit of the gas-air mixture from the breathing valve through the pressure plate, half open, can be seen in Figure 3.6.

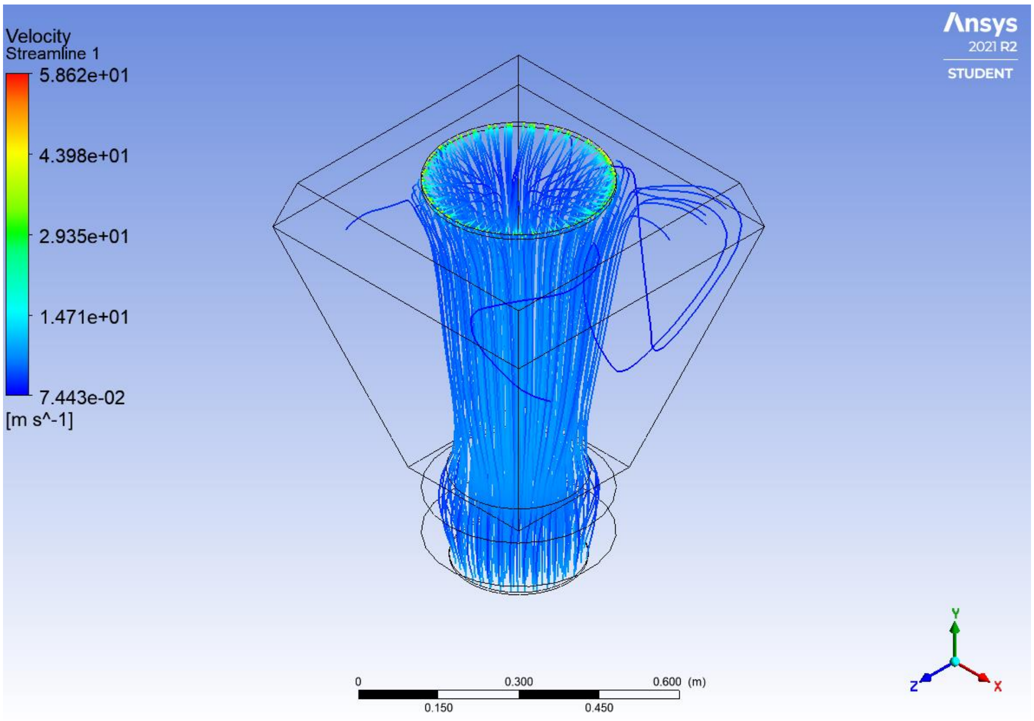
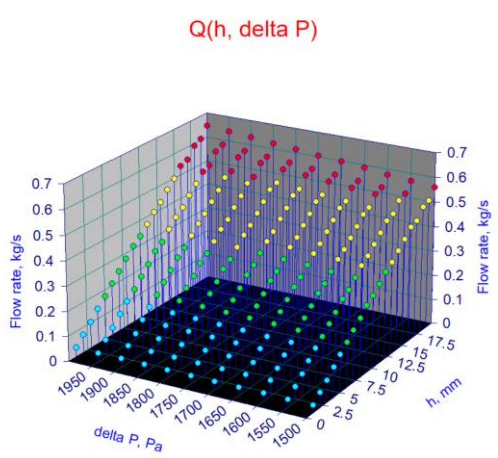
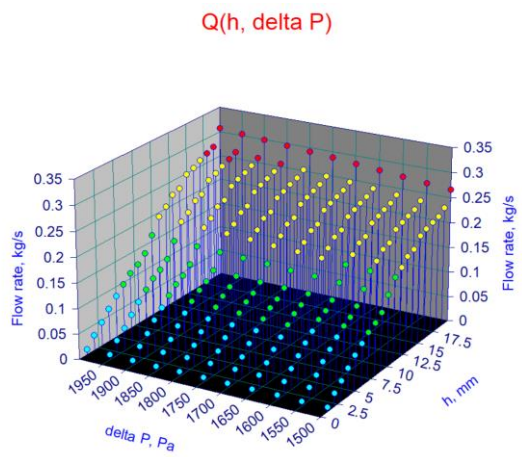



*Figure 3.6 The model of the gas-air mixture outlet through a half-open pressure plate*

According to the values of appendices A and B, graphs of points were obtained (Figure 3.7).




a) the pressure plate is fully open




b) the pressure plate is half open

*Figure 3.7 The graphical representation of the distribution of dependence Q (ΔP, h)*

## 3.2 Calculation part

To determine the formula, tools such as:

a) TableCurve 3D;

b) Excel tool (search for a solution using the downward gradient method);

c) Least squares method;

d) The equation of the plane.

### 3.2.1 TableCurve 3D computer program

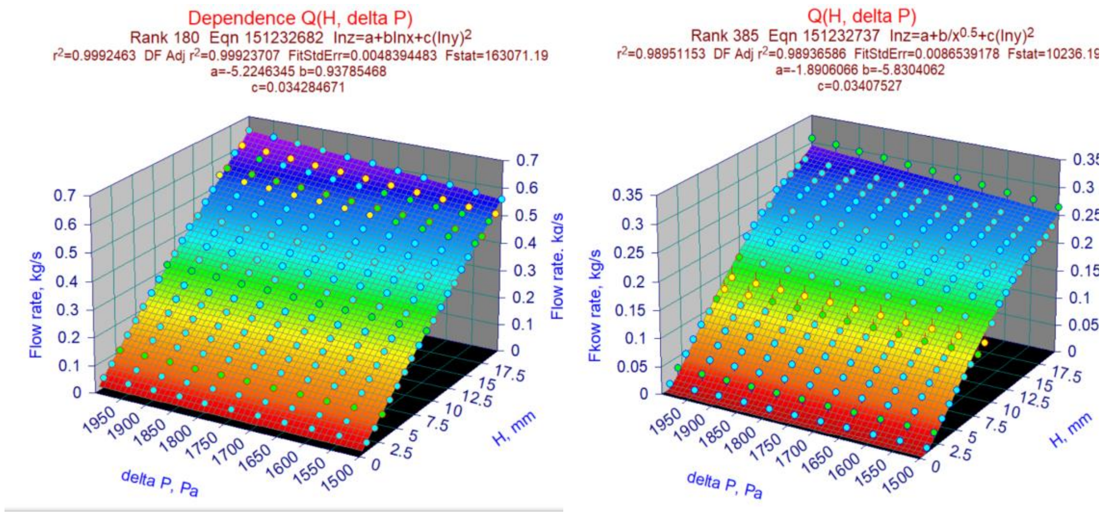
As can be seen from Figure 3.4, the function *Q (ΔP, h)* will have a linear dependence. So, with the help of the computer program Table Curve 3D, equations were selected that describe as accurately as possible the distribution of mass flow points presented above, the graph of which can be observed in Figure 3.8:

$$\ln Q = -5,2246345 + 0,93785468 \cdot \ln h + 0,034284671(\ln \Delta P)^2 \quad (3.1)$$

$$\ln Q = -1,8906066 - \frac{5,8304062}{h^2} + 0,03407527(\ln \Delta P)^2 \quad (3.2)$$

where *h* – the height of lifting the pressure cap, mm;

$\Delta P$ – excess pressure in the tank, Pa.




a) the pressure plate is fully open b) the pressure plate is half open

*Figure 3.8 The llinear functions Q($\Delta P$, h) obtained in TableCurve 3D*

As can be observed with the help of the program, equations were selected for the function $Q$ ($\Delta P$, $h$) with a sufficiently high coefficient of determination, $r^2$ = 0.999 for a fully open plate and $r^2$ = 0.989 for a pressure plate open to the middle.

## 3.2.2 The "Solution Search" function in Excel

With the help of the "Solution Search" function located in Excel, formulas such as:

$$Q = k \cdot h \cdot \Delta P \tag{3.3}$$

where $k$ is a free term selected using the Excel function "Search for a solution".

For a more accurate finding of the free term $k$, all calculations were carried out using the average values of $h$ (the height of the pressure plate opening) and the average pressure drop $\Delta P$ in all experiments. Figure 3.9 shows the necessary parameters for using the function.

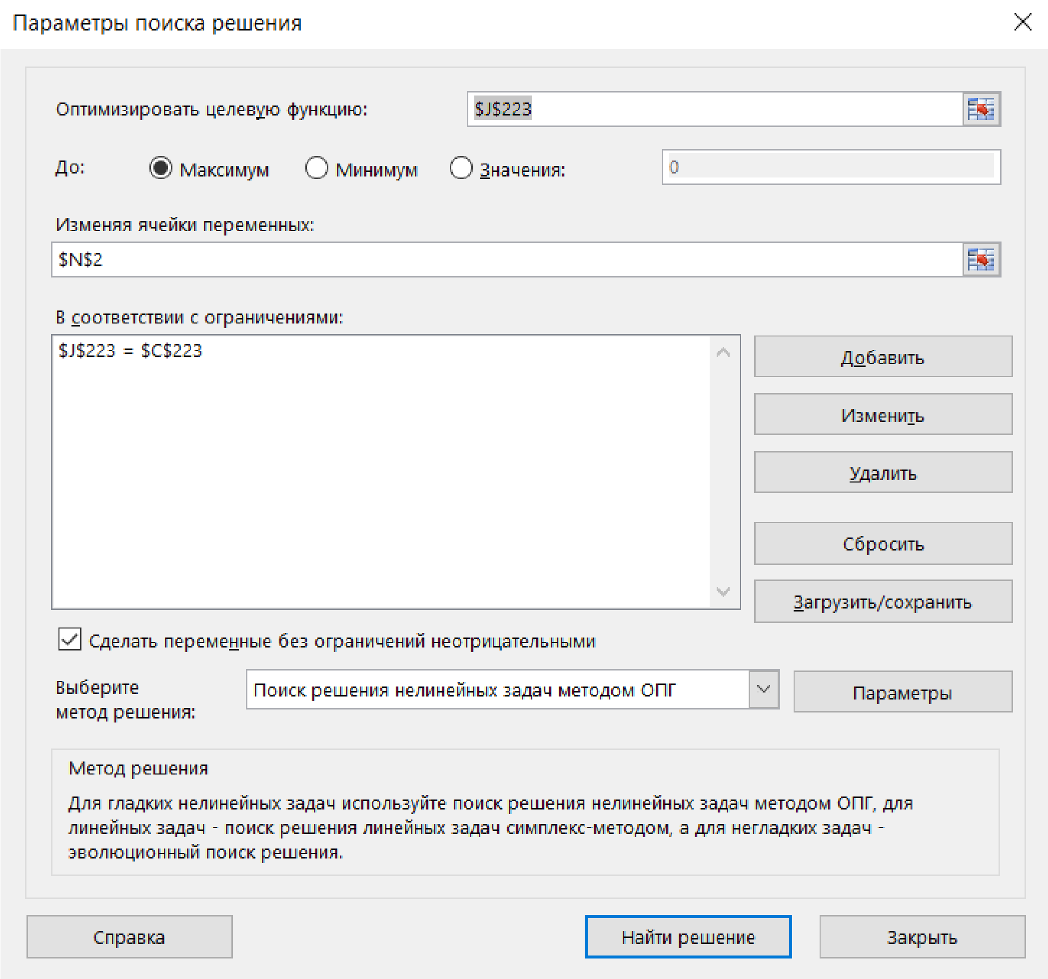



*Figure 3.9 Solution Search parameters window*

The function $Q = k \cdot h \cdot \Delta P$ acts as the objective function $J$223. The variable cell is just the value of the resulting function, and the limitation of the solutions was set such that the resulting function should be equal to the average value of the stroke obtained as a result of the calculations performed on the breathing valve (Figure 3.6).

Thus, the functions $Q\ (\Delta P, h)$ were obtained for two cases, in accordance with equation 3.3:

$$Q = 179,5 \cdot 10^{-7} \cdot h \cdot \Delta P$$

$$Q = 8,41 \cdot 10^{-6} \cdot h \cdot \Delta P$$

The coefficients for a linear function of the form were obtained by the same method:

$$Q = a \cdot h + b \cdot \Delta P \qquad (3.4)$$

As a result, using the "Solution Search" function, the following equations 3.4 were obtained:

$$Q = 1{,}118 \cdot 10^{-6} \cdot h + 1{,}864 \cdot 10^{-4} \cdot \Delta P$$

$$Q = 5{,}299 \cdot 10^{-7} \cdot h + 8{,}831 \cdot 10^{-5} \cdot \Delta P$$

When using the "Solution Search" function to find unknown terms of the function in power and exponential, the solution was reduced to the function $Q = k \cdot h \cdot \Delta P$, so they will not be considered in the future.

### 3.2.3 Least squares method

Using this method, coefficients *a* and *b* were selected for an equation of the form (3.4).

1) The essence of the method is that first you need to find an approximating function:

$$y = Q(h, \Delta P, a, b) \tag{3.5}$$

To determine the coefficients *a* and *b* in the function in point 1, the deviations between the desired function and the table values at points xi of the deviation were the smallest.

2) Select the values of the coefficients *a* and *b* so that the sum of the squares of the deviations is minimal:

$$S(a,b) = \sum_{i=1}^{n} (\Delta y_i)^2 = \sum_{i=1}^{n} [Q(h, \Delta P, a, b) - y_i]^2 \to \min \tag{3.6}$$

3) We make up a system of equations such that $S'_a = 0$, $S'_b = 0$:

$$\begin{cases} S'_a(a,b) = \sum_{i=1}^{n} 2(ah_i + b\Delta P_i - y_i) \cdot h_i = 0 \\ S'_a(a,b) = \sum_{i=1}^{n} 2(ah_i + b\Delta P_i - y_i) \cdot \Delta P_i = 0 \end{cases} \tag{3.7}$$

4) Transform the system into the following form:

$$\begin{cases} a \cdot (\sum_{i=1}^{n} h_i^2) + b \cdot (\sum_{i=1}^{n} \Delta P_i \cdot h_i) = \sum_{i=1}^{n} y_i \cdot h_i \\ a \cdot (\sum_{i=1}^{n} \Delta P_i \cdot h_i) + b \cdot (\sum_{i=1}^{n} \Delta P_i^2) = \sum_{i=1}^{n} \Delta P_i \cdot y_i \end{cases} \tag{3.8}$$

5) To determine the coefficients *a* and *b*, you need to solve several matrices

$$\Delta = \begin{vmatrix} \sum_{i=1}^{n} h_i^2 & \sum_{i=1}^{n} \Delta P_i \cdot h_i \\ \sum_{i=1}^{n} \Delta P_i \cdot h_i & \sum_{i=1}^{n} \Delta P_i^2 \end{vmatrix} \tag{3.9}$$

$$\Delta_a = \begin{vmatrix} \sum_{i=1}^{n} y_i \cdot h_i & \sum_{i=1}^{n} \Delta P_i \cdot h_i \\ \sum_{i=1}^{n} \Delta P_i \cdot y_i & \sum_{i=1}^{n} \Delta P_i^2 \end{vmatrix} \tag{3.10}$$

$$\Delta_b = \begin{vmatrix} \sum_{i=1}^{n} h_i^2 & \sum_{i=1}^{n} y_i \cdot h_i \\ \sum_{i=1}^{n} \Delta P_i \cdot h_i & \sum_{i=1}^{n} \Delta P_i \cdot y_i \end{vmatrix} \tag{3.11}$$

6) Then the coefficients *a* and *b* are calculated as follows:

$$a = \frac{\Delta_a}{\Delta} \tag{3.12}$$

$$b = \frac{\Delta_b}{\Delta} \tag{3.13}$$

Calculation example for a fully open pressure plate:

To begin with, we will write down all the necessary amounts and bring it all into one table 3.2.

*Table 3.2 Sums of experimental data from point 4*

| $\sum_{i=1}^{n} h_i^2$ | $\sum_{i=1}^{n} \Delta P_i \cdot h_i$ | $\sum_{i=1}^{n} y_i \cdot h_i$ | $\sum_{i=1}^{n} \Delta P_i^2$ | $\sum_{i=1}^{n} \Delta P_i \cdot y_i$ |
|---|---|---|---|---|
| 31570 | 4042500 | 971,963 | 679250000 | 126143 |

Then the system of equations from equation (3.8) will look like this:

$$\begin{cases} 31570 \cdot a + 4042500 \cdot b = 971{,}963 \\ 4042500 \cdot a + 679250000 \cdot b = 126143 \end{cases}$$

To determine the coefficients *a* and *b*, you need to solve the following matrices (3.8-3.11):

$$\Delta = \begin{vmatrix} 31570 & 4042500 \\ 4042500 & 679250000 \end{vmatrix} = 5{,}1021 \cdot 10^{12},$$

$$\Delta_a = \begin{vmatrix} 971{,}963 & 4042500 \\ 126143 & 679250000 \end{vmatrix} = 1{,}503 \cdot 10^{11},$$

$$\Delta_b = \begin{vmatrix} 31570 & 971{,}963 \\ 4042500 & 126143 \end{vmatrix} = 21590646.$$

Substitute the resulting values in equations 3.12 and 3.13:

$$a = \frac{1{,}503 \cdot 10^{11}}{5{,}1021 \cdot 10^{12}} = 0{,}02945,$$

$$b = \frac{21590646}{5{,}1021 \cdot 10^{12}} = 4{,}2 \cdot 10^{-6}.$$

We do the same steps for the case when the pressure plate is half open, and then we get the following formulas for flow through the breathing valve $Q$ ($\Delta P$, $h$):

$$Q = 0{,}02945 \cdot h + 4{,}2 \cdot 10^{-6} \cdot \Delta P$$

$$Q = 0{,}0142 \cdot h + 3{,}4 \cdot 10^{-6} \cdot \Delta P$$

## 3.2.4 Equation of the gas-air mixture flow through the plane

In order to obtain an equation of the plane that will describe the dependence $Q$ ($\Delta P$, $h$), it is necessary to determine three points through which the plane will pass: $A$ ($x_0$; $y_0$; $z_0$), $B$ ($x_1$; $y_1$; $z_1$) и $C$ ($x_2$; $y_2$; $z_2$).

1) Let's make the following matrix:

$$\begin{vmatrix} x - x_0 & y - y_0 & z - z_0 \\ x_1 - x_0 & y_1 - y_0 & z_1 - z_0 \\ x_2 - x_0 & y_2 - y_0 & z_2 - z_0 \end{vmatrix} = 0 \qquad (3.14)$$

2) Next, solve the matrix:

$$(x-x_0)\cdot\begin{vmatrix} y_1-y_0 & z_1-z_0 \\ y_2-y_0 & z_2-z_0 \end{vmatrix}-(y-y_0)\cdot\begin{vmatrix} x_1-x_0 & z_1-z_0 \\ x_2-x_0 & z_2-z_0 \end{vmatrix}+(z-z_0)\cdot\begin{vmatrix} x_1-x_0 & y_1-y_0 \\ x_2-x_0 & y_2-y_0 \end{vmatrix} \tag{3.15}$$

3) We obtain an equation of the form:

$$z=a\cdot x+b\cdot y \tag{3.16}$$

Example of calculation on a breathing valve with a fully open pressure plate. We take the following points: *A* (0; 0; 0) – the origin, *B* (10.5; 1750; 0.3263) – the average values and *C* (20; 2000; 0.6476) – the last point.

We make up the matrix, as in equation (3.14):

$$\begin{vmatrix} x & y & z \\ 10,5 & 1750 & 0,3263 \\ 20 & 2000 & 0,6476 \end{vmatrix}=0$$

Solve the matrix and get the following equation:

$$Q=0,0343\cdot h+1,956\cdot 10^{-5}\cdot\Delta P$$

And in the same way we determine the equation for a pressure plate open by half:

$$Q=0,0163\cdot h+9,5\cdot 10^{-6}\cdot\Delta P$$

# 3.2.5 Analysis of the formulas obtained

As a result of the mathematical calculations carried out, several variants of the formulas were obtained, which are presented above. To determine the most appropriate formula, we calculate the standard deviation and choose the formula that has the smallest value.

To calculate the standard deviation, first you need to calculate the arithmetic mean of the results of n measurements:

$$\overline{X}=\frac{\sum_{i=1}^{n} x_i}{n} \tag{3.17}$$

Then the standard deviation will be calculated by the formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{X})^2}{N}} \tag{3.18}$$

Using the example of one calculation, for the formula obtained using the TableCurve 3D program for a fully open pressure plate, fill in Table 3.3.

The average flow rate for a fully open pressure plate is:

$$\overline{X} = \frac{0,0315 + 0,0608 + ... + 0,6047 + 0,6476}{220} = 0,3263$$

Then the standard deviation will be equal to:

$$\sigma = \sqrt{\frac{(0,03368 - 0,3263)^2 + ... + (0,6477 - 0,3263)^2}{220}} = 0,1726$$

*Table 3.3 Standard deviations for the formulas obtained*

| The degree of the opening of the pressure plate | Method of obtaining the equation | | | | |
|---|---|---|---|---|---|
| | Excel ($Q=a\cdot h+b\cdot \Delta P$) | Excel ($Q=k\cdot h\cdot \Delta P$) | Table Curve 3D | LSM | Equation of the plane |
| Fully open | 0,0295 | 0,1847 | 0,1726 | 0,1705 | 0,198 |
| Half open | 0,0139 | 0,0864 | 0,0847 | 0,0819 | 0,0939 |

Analyzing Table 3.3, the most accurate formula for the dependence Q (ΔP, h), in both cases, is obtained using the "Solution Search" function in Excel, since there is the smallest standard deviation.

But to make a final choice, let's analyze the physical meaning of the formulas.

If you set the formula for the dependence $Q$ ($\Delta P$, $h$) through the equation of the plane passing through the origin, which characterizes zero flow at zero values of overpressure and the height of the pressure plate lifting, or through the formula obtained using the "Solution Search" function, these formulas have one common drawback.

Since these formulas are of the form $Q = a\cdot h+b\cdot \Delta P$, there is one problem.

Since the pressure plate is triggered only at an overpressure greater than 1500 Pa, then up to this point, the formula will not produce the correct flow rate, that is, at an overpressure of, for example, 500 Pa, the pressure plate will be closed ($h$ = 0), and the flow rate will be 500 · $b$, although it should be zero. The same effect will be observed if the overpressure is zero and the pressure plate is open.

When using a formula obtained using TableCurve 3D with zero values of one of the components, the formula will not be able to be calculated at all.

In this case, the most correct formula from a physical point of view is $Q = k \cdot h \cdot \Delta P$, since with a zero value of one of the terms ($h$ or $\Delta P$), there will be no flow through the breathing valve, which reflects reality.

Therefore, despite the correct physical meaning of formulas of the form $Q = k \cdot h \cdot \Delta P$, for a fully open pressure plate and half with a standard deviation equal to 0.1847 and 0.0864, respectively, it was decided to use formulas of the form $Q = a \cdot h + b \cdot \Delta P$ to calculate the flow through the breathing valve, since they have the smallest standard deviation of all the formulas analyzed.

Formulas for determining the mass flow through the breathing valve depending on the degree of opening of the pressure plate and overpressure $Q$ ($\Delta P$, $h$):

- The mass flow through fully open pressure plate

$$Q = 0{,}02945 \cdot h + 4{,}2 \cdot 10^{-6} \cdot \Delta P$$

- The mass flow through half open pressure plate

$$Q = 0{,}0142 \cdot h + 3{,}4 \cdot 10^{-6} \cdot \Delta P$$

## 3.3 Description of the method for determining the amount of oil product vapors from the tank through the breathing valve

An optical multi-channel sensor for determining the concentration of hydrocarbons in the tank’s GS will be installed inside the tank, which will determine the concentration of LFH every second when the valve is triggered. This device can be installed at any point of the tank, the main thing is above the level of product take-off.

Also, a pressure sensor will be located on the tank, measuring the exact pressure of the gas-air mixture inside the tank. A sensor will be installed on the pressure plate, which will measure both the height of elevation and the angle of inclination, for more accurate calculations of losses from evaporation.

The closest inventions to this technique are the developments (Zemenkov Yu.D., Levitin R.E., Dyakov K.V., 2014; Buzenkov O.P., Kabanov V.I., Mironov N.A., Molchanov O.V., Novikov M.V., 2013; Molchanov O.V., Navmatullin A.Z., Khudynin S.V., Dmitriev S.V., Kabanov V.I., 2020). The developed methodology takes into account all the shortcomings that were present in the above-mentioned inventions.

The essence of the technique is that when the breathing valve is triggered, that is, when the pressure plate is opened, the optical concentration sensor will measure every second the concentration of LFH contained in the gas tank and exiting through the breathing valve, the overpressure sensor will measure the pressure inside the tank, and the position of the pressure plate will be recorded every second using an accelerometer, which in the future will be useful for calculating the flow of LFH through the breathing valve according to the formulas obtained above.

Thus, the mass flow rate of the gas-air mixture through the breathing valve will be calculated using the following formulas:

$$Q_{гвс} = \sum Q_i, [kg / s] \qquad (3.19)$$

where $Q_{газ}$ – the total mass flow rate of the gas-air mixture through the breathing valve, kg/s;

$Qi$ – the mass flow rate of the gas-air mixture in the $i$-th second, calculated by the formula $Q(\Delta P, h)$, kg/s.

Where the mass of LFH is calculated by the formula:

$$m_i = Q_i \cdot t \cdot C_i, [kg] \qquad (3.20)$$

where $m_i$ – the mass of the gas-air mixture in the $i$-th second, kg;

$t$ – 1 second, s;

$C_i$ – the concentration of LFH in the $i$-th second coming out of the breathing valve, measured using an optical gas analyzer, %.

Accordingly, the total losses for the entire period of opening the pressure cap will be calculated according to the formula:

$$m = \sum m_i, [kg] \quad (3.21)$$

## 3.4 Experimental setup

For safety and in order to increase the speed of the experiment, it was decided to conduct experiments with water.

A small container of water, pre-weighed, was heated on a stove to accelerate evaporation from the surface of the liquid.

Two Arduino sensors were also used for the experiment: the BMP280 pressure and temperature sensor and the SI7021 temperature and humidity sensor (I2C).

When the liquid was boiling, the pressure inside and outside the container, the temperature inside and outside, as well as the humidity of the liquid, that is, its concentration, were recorded. The lid was opened periodically to simulate the operation of the breathing valve; you can see a sketch of experiment below (Figure 3.10) left side of picture  container lid is closed and the right side  open.

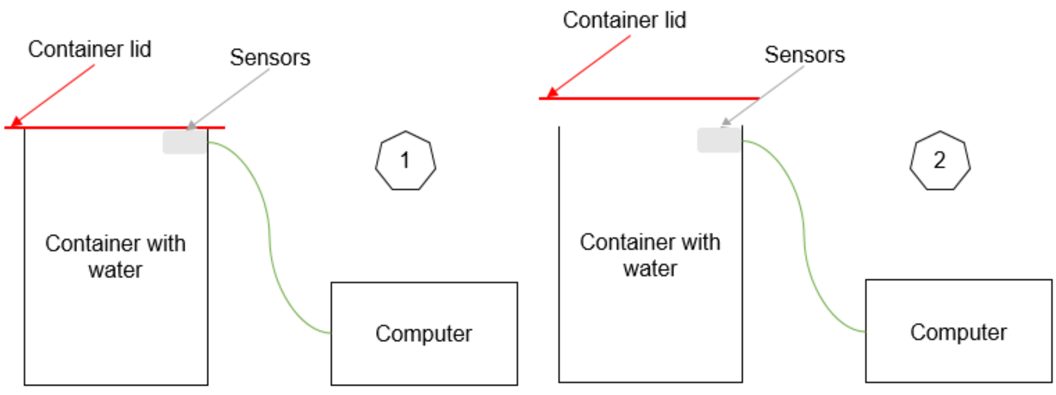



*Figure 3.10 A sketch of experiment*

Previously, an experiment was modeled in the Ansys software package to determine the steam flow through the opened lid.

After the experiment, the container was weighed again, so the exact amount of evaporated liquid was calculated, calculations were also carried out using the proposed methodology and thus the error was calculated.

With the help of a code that can be viewed in Appendix B, the readings were taken from the sensors and recorded in the console (Figure 3.11).

Below you can see a simplified view of the code, presented in the form of a flowchart (Figure 3.12).

Nine experiments were conducted with water to determine the error of readings obtained using sensors. The difference in suspended water before and after the experiment on the kitchen scales was taken as true readings.

In Appendix C presents data from one of the nine experiments that were necessary to calculate the evaporated water.

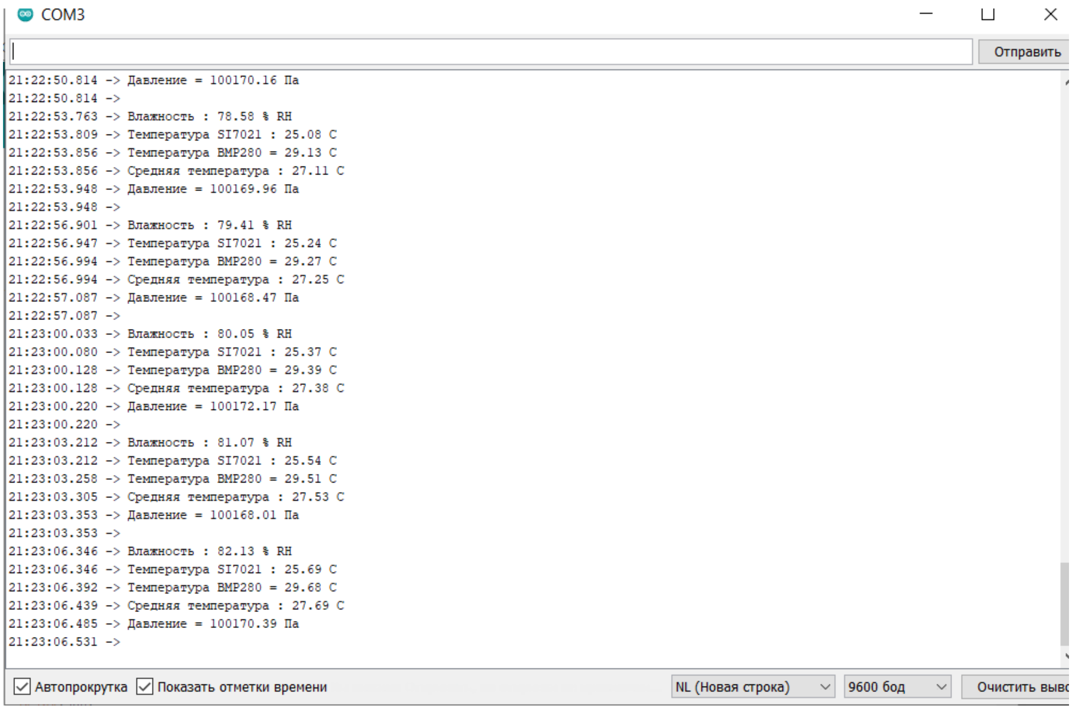



*Figure 3.11 An example of recordi ng data from sensors in the console*

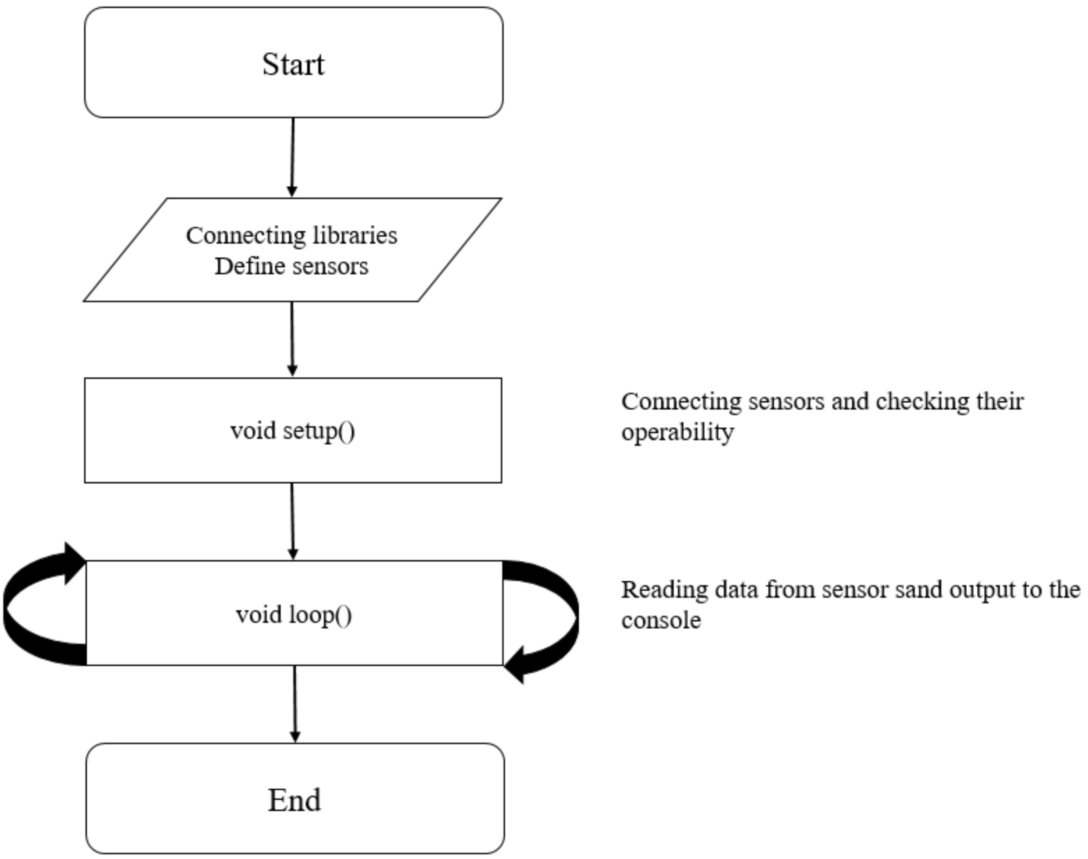



*Figure 3.12 A block diagram for the code*

The course of all experiments will be described below using the example of the first one.

The course of the experiment:

1) Weigh the water before the experiment $m_1$ = 595 g;

2) Heat the water in the vessel to 50 C on the gas stove until the humidity sensor shows 100 %;

3) Lift the lid of the vessel and measure the humidity and temperature after opening;

4) Enter the data in the table;

5) Weigh the water after the experiment $m_2$ = 532 g;

6) Make calculations based on the sensor readings;

7) Compare $m_{весы}$ and $m_{датчик}$.

In this experiment, it was determined using kitchen scales that the mass of evaporated water was $m_{весы}$ = 63 g.

The calculation of the mass of evaporated water was as follows:

The column under number 1 shows the experiment number, that is, the amount of lifting of the lid of the vessel for releasing steam. The second and fourth columns record the temperatures at which the lid was opened and closed, that is, the beginning and end of the experiment. Columns 3 and 5 record the densities of saturated water vapor at temperatures in columns 2 and 4, which were taken from the tables (Appendix C). Further, in columns numbered 8 and 9, the masses of water vapor contained in the vessel before and after the experiment (lifting the lid) were recorded, which were calculated according to the following formula:

$$\varphi = \frac{\rho}{\rho_к} \tag{3.22}$$

where ρ – the density of unsaturated steam, g/m$^3$;

$\rho_k$ – the saturated vapor density, tabular value, g/m$^3$.

Example of calculation for the first row (experiment) in the first experiment using equation 3.22:

$$\rho = \rho_к \cdot \varphi = 67{,}1 \cdot 0{,}7 = 47 g / m^3$$

To determine the mass of saturated steam at the beginning, it is required to multiply the density of saturated steam at the beginning by the volume of the vessel, which is V = 0.053066 m$^3$.

The mass of water vapor in the vessel before lifting the lid, column 8:

$$m = V \cdot \rho = 0{,}053066 \cdot 83 = 4{,}4 g$$

The mass of water vapor in the vessel after lifting the lid, column 9:

$$m = V \cdot \rho = 0{,}053066 \cdot 47 = 2{,}5 g$$

Mass of vaporized steam, column 10:

$$\Delta m = 4{,}4 - 2{,}5 = 1{,}9 g$$

The same should be done for each experiment (lifting the lid) throughout the experiment. And by adding one with the other, we get the mass of steam released when opening the lid, that is, the mass of evaporated water during the experiment, which is the $m_{датчик}$ = 51.3 g.

The relative error is calculated by the formula:

$$\varepsilon = \frac{|m_{весы} - m_{датчик}|}{m_{датчик}} \cdot 100\% = \frac{|63 - 51,3|}{51,3} \cdot 100\% = 22,85\% \qquad (3.23)$$

Nine such experiments were carried out and for each the mass of evaporated water was calculated during the experiment and then the relative error was calculated, which for ease of understanding was summarized in Table 3.4.

*Table 3.4 Relative errors in experiments*

| № | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| ε | 22,85 | 31,19 | 25,62 | 24,25 | 22,61 | 23,18 | 28,43 | 26,15 | 23,15 |

The average value of the relative error in the end is:

$$\bar{\varepsilon} = \frac{22,85 + 31,19 + 25,62 + 24,25 + 22,61 + 23,18 + 28,43 + 26,15 + 23,15}{9} = 25,27\%$$

Considering that the BMP280 and SI7021 sensors have more errors than the sensors in production, it can be judged that the system will work more accurately if industrial sensors are used.

Thus, it has been experimentally proved that instrumentally in the automatic mode, it is possible to calculate the evaporation of water from the vessel, and, consequently, by the same method, it is possible to calculate the evaporation of oil and petroleum products from tanks through the breathing valve as a result of large and small breaths.

## 3.5 Selection of equipment for automatic accounting of vapors

For the proposed methodology, it is possible to use already existing and used in the industry devices: an overpressure measurement sensor, an LFH concentration sensor and a position control sensor in space.

## 3.5.1 Overpressure sensor.

Since to calculate the flow rate of the gas-air mixture, it is necessary to know the value of $\Delta P$, that is, the pressure difference inside and outside the tank, then a pressure gauge can be used to measure this value, which will show the overpressure, that is, just the required difference.

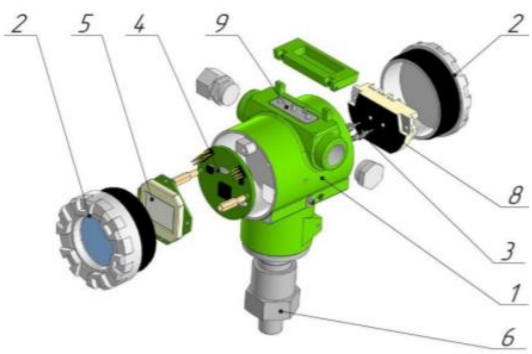
To measure the overpressure, an EMIS BAR 103 Exd overpressure sensor in explosion-proof design can be used.

Sensor Characteristics:

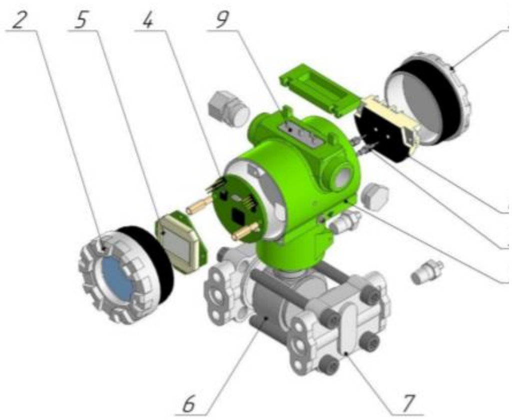
- Full measurement range (-100...100 kPa);
- Minimum upper limit of measurements (1 kPa);
- Operating temperature range (-60...+120 0C).

The pressure sensor (Figure 3.13) was selected in such a way that it was possible to remotely monitor and measure readings for automatic accounting of vapors from the tank as a result of large and small breaths.

The principle of operation of the sensor for measuring excess pressure EMIS BAR is based on a piezoresistive pressure measurement method based on pressure changes as a result of deformation of the sensing element, which is monocrystalline silicon. The sensing element is fixed on a silicon substrate, which is fixed on a sensitive membrane. As a result of the pressure change, the resistance geometry of the Wheatstone bridge and the potential difference at its outputs change. After the necessary transformations, signal amplification, filtration at the output, we obtain a proportional change in pressure.




a) Sensor of fitting design




b) Flanged sensor

1 housing; 2 caps with seal; 3 RFI filters; 4 electronic circuit board; 5 LCD modules; 6 pressure converter; 7 flange; 8 terminal block; 9 sensor adjustment buttons.

*Figure 3.13 The device of pressure sensors*

The sensor shown in Figure 3.12a is ideal for the proposed technique. The overpressure sensor will be located on the roof of the tank in such a way that its lower part (the fitting) will be in the GS of the tank.

### 3.5.2 Concentration measurement sensor.

At the moment, there is a huge selection of sensors on the market that register the concentration of controlled substances. Optical sensors are now gaining popularity in use, as they are easy to use and safe.

For example, a multi-channel optical gas analyzer was selected for the automatic method of accounting for oil product vapors, which will be installed directly inside the tank and will measure the concentration of the outgoing gas-air mixture every second while the valve is in operation.

Optical concentration sensors have been designed to work in a wide range of trapping, so they are used for low concentrations of controlled substances. The principle of operation of these gas analyzers is based on the phenomenon of selective absorption of radiation energy of a certain wavelength by the analyzed components, and the intensity of this absorption depends on the concentration of the analyzed component.

Each gas has its own absorption spectrum, at a certain wavelength. Sometimes the spectra of gases intersect, but when using a different wavelength, which has a selective absorption of IR radiation, it is possible to minimize the error in determining the gas and so use this type of GA to determine the concentration in a multicomponent mixture.

The gas-air mixture enters the optical GA chamber, where it is exposed to pulsed infrared radiation of a certain wavelength. If there is a gas in the introduced gas-air mixture that absorbs a given wavelength, then the photodetector will receive such an amount of radiation that will be equal to the initial radiation minus the radiation absorbed by the gas. The amount of radiation absorbed by the gas will be equal to the concentration of gas in the analyzed medium.

The design of the optical sensor contains an optically transparent cuvette through which gas continuously passes, and an optical system consisting of an emitter and a photodetector (Figure 3.14). The emitter generates pulsed infrared radiation, it passes through the cuvette, is partially absorbed by a certain component and the remaining radiation enters the photodetector. The radiation is usually generated by LEDs.

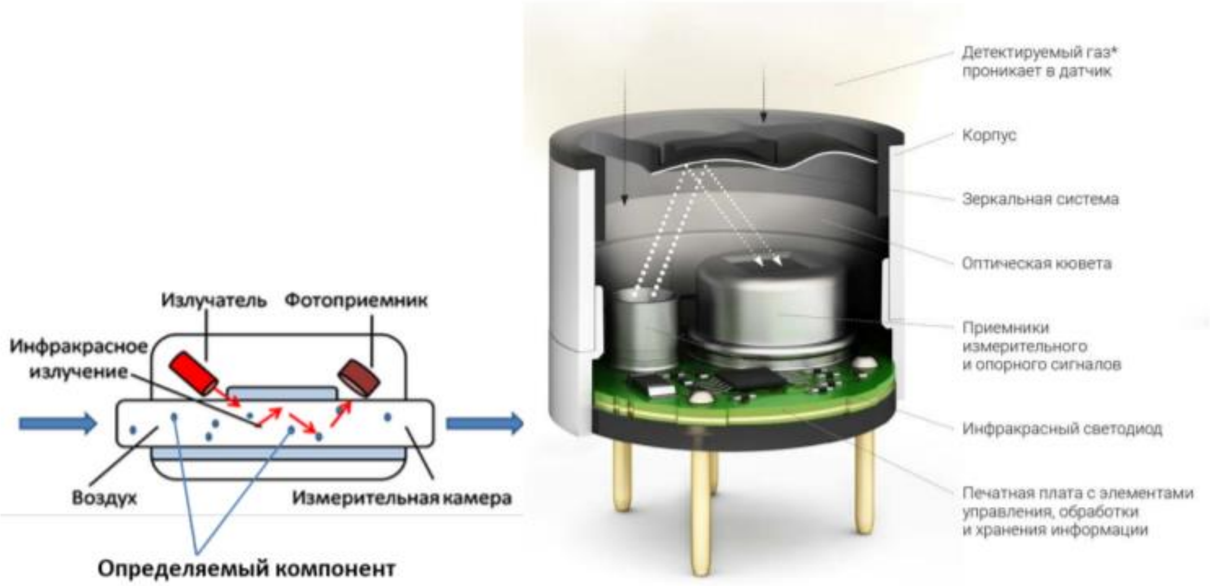



*Figure 3.14 Optical sensor. The principle of operation and design*

Based on the principle of operation of the optical gas analyzer, it can be concluded that it is possible not to measure the density of the gas, and not to make adjustments for concentration, since all this has already been taken into account in the principle of operation of the gas analyzer.

The Russian-made gas analyzer ИДК-10-Х1 will cope well with this task (Figure 3.15). It is designed in an explosion-proof design, the operating temperature range is from -60 to +65 degrees Celsius. In the line of gas analyzers there are models that determine the concentration of gasoline vapor AI 92, AI 95, diesel fuel, kerosene for rocket engines, kerosene for gas turbine engines, aviation gasoline, as well as other gases.

*Figure 3.15 ИДК-10-X1 gas analyzer*

This gas analyzer measures gasoline vapors in the range from 0 to 50 LCLFP (lower concentration limit of flame propagation).

## 3.5.3 Sensor pressure plate position

To measure the position of the pressure plate, you need a device that will measure both the vertical movements of the plate and the angle of inclination. The accelerometer will perfectly cope with such a task.

An accelerometer is a device that, thanks to its sensitive mass, determines the projection of free acceleration, thereby it is possible to calculate movements.

There are MEMS accelerometers (microelectromechanical systems), this type of accelerometer will be used in the method (Figure 3.16), which must be connected to a spectrum analyzer.

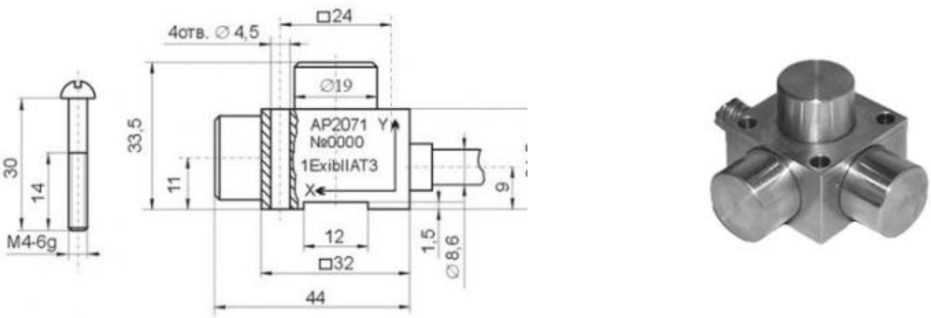


*Figure 3.16 An accelerometer AR2071 (AR71)*

## 3.6 Location of sensors

All sensors for ease of maintenance and connection will be located in one place with only one difference, one group of sensors will be located outside the tank, and the other inside the tank.

To do this, you will need to make a hatch, measuring 30x30 cm, in the roof of the tank near the breathing valve, on which temperature and overpressure sensors will be installed on top and a concentration sensor will be installed inside, and an accelerometer will be installed directly on the pressure plates of the breathing valve to measure the position.

A hole will be made in the sensor hatch for installing a temperature sensor, which will have only a sensitive element inside the tank, with which the temperature will be determined, and all the connection channels and the information output device will be located on the surface of the tank roof. Also, to protect against weather conditions, the sensor will be located in a protective casing.

A flange will be located nearby, to which the sensitive membrane of the overpressure sensor will be attached. The sensor itself will be mounted on a vertical mounting tube, to which it will be attached using a bracket. The pressure sensor will be located at a height of 20-30 cm from the attachment point of the sensitive membrane for correct operation, the principle of location is approximately shown in Figure 3.17, and also for protection from weather conditions, the sensor will be located in a protective casing.

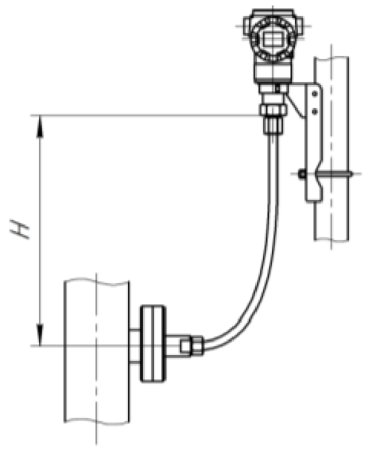



*Figure 3.17 A location of the pressure sensor*

The concentration sensor will be mounted at the bottom of this hatch, since the sensitive element must be in a controlled/measured environment. On the back side of the hatch, a metal frame will be mounted in the form of a pipe perpendicular to the surface of the hatch, to which the concentration sensor will be attached, or you can mount the frame in the form of a plane to which the sensor will be attached, so it will even be easier to install and maintain in the future. For the channels of connection and output of data from the concentration sensor, a hole will be made in the hatch, which will be sealed at the time of operation of the sensor.

The hatch is necessary for compact placement of all sensors in one place, this will facilitate repair work, verification work and maintenance of sensors.

## 3.7 Conclusions. Chapter results.

In the course of the work done in this section, the following works were carried out and the following results were obtained:

1. Initially, the CBV 1500/150 breathing valve with a fire barrier was modeled in КОМПАС 3D. In order to simplify the calculations in the Ansys program, the valve was divided into two hydraulic units: the fire starter and the valve itself. As a result, pressure characteristics were obtained for both objects and components, since the losses of the fire barrier compared to the valve are small, then they were not taken into account

2. Equations for the flow through the breathing valve are obtained depending on the degree of opening of the pressure plate and the excess pressure $Q\ (h, \Delta P)$ for the fully open plate and half.

3. A new methodology and system for monitoring and accounting for LFH losses from vapors from tanks in real time has been developed.

4. An experiment with water has been carried out, which shows that instrumentally the method can be used in production to calculate the losses of LFH through the breathing valve in automatic mode.

5. The equipment is selected and recommendations for its installation and use are given.

# Chapter 4

# Conclusion

## 4.1 Summary

A review of the literature on this topic showed that the topic is relevant and there is currently no automated monitoring of data on the concentration of outgoing LFH in real time.

Thus, the purpose of the master's study was to develop a new methodology and a system for monitoring and accounting for LFH losses from evaporation from tanks in real time.

Based on the Ansys software package, a model of a breathing valve was built and the flow rate of the gas-air mixture was calculated depending on the degree of opening of the pressure plate and the pressure difference (internal and atmospheric), and a model of an experimental installation was built.

Formulas are obtained for the flow through the breathing valve depending on the degree of opening of the pressure plate and the overpressure $Q$ ($h$, $\Delta P$) for the fully open plate and half.

An experiment was conducted with water and Arduino sensors, which shows that instrumentally the method can be used in production to calculate LFH losses through a breathing valve in automatic mode.

The equipment was selected and recommendations for its installation and use were given.

## 4.2 Evaluation

The work has been done qualitatively and corresponds to the set goals. The theoretical part has been done and disassembled 100 %. The only drawback of the work is that it was not carried out by experience on a real model of a breathing valve with real sensors in order to assess the actual measurement error obtained using the proposed technique. This barrier appeared due to the fact that there are no funds and access to industrial conditions and technologies.

## 4.3 Future Work

There were some imperfections and shortcomings in the works in which methods close to the one being developed were proposed. For example, in work (Zemenkov Yu.D., Levitin R.E., Dyakov K.V., 2014) a flow meter was installed that did not work at low temperatures, and in work (Molchanov O.V., Navmatullin A.Z., Khudynin S.V., Dmitriev S.V., Kabanov V.I., 2002) a concentration sensor is installed directly in front of the breathing valve, which also affects the flow rate, but this was not taken into account in the work.

The proposed technique is close to (Molchanov O.V., Navmatullin A.Z., Khudynin S.V., Dmitriev S.V., Kabanov V.I., 2002), only in the developed technique the concentration sensor is installed next to the breathing valve, which does not affect the flow rate, and specific sensors and their installation locations are also proposed.

The disadvantage of the technique is that a small assumption is made that the concentration in the tank is constant everywhere at any given time, and the operation of two breathing valves and more has not been considered, which can be done in further developments.

Also, in future studies, it is necessary to validate the obtained formulas by conducting an experiment using an active breathing valve and in conditions close to real ones.

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# Appendix A

## Dependence of the mass flow rate on the degree of opening of the lid and the pressure difference

*Table 0.1 Mass flow rate of the vapor-air mixture through the fully open lid*

| The degree of opening of the pressure plate h, mm | Mass flow rate through the pressure plate Q, kg/s | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ΔP=1500, Pa | ΔP=1550, Pa | ΔP=1600, Pa | ΔP=1650, Pa | ΔP=1700, Pa | ΔP=1750, Pa | ΔP=1800, Pa | ΔP=1850, Pa | ΔP=1900, Pa | ΔP=1950, Pa | ΔP=2000, Pa |
| 1 | 0,0315 | 0,0321 | 0,0326 | 0,0331 | 0,0336 | 0,0341 | 0,0346 | 0,0352 | 0,0358 | 0,0360 | 0,0366 |
| 2 | 0,0608 | 0,0618 | 0,0628 | 0,0638 | 0,0648 | 0,0658 | 0,0667 | 0,0677 | 0,0687 | 0,0698 | 0,0706 |
| 3 | 0,0890 | 0,0904 | 0,0919 | 0,0933 | 0,0948 | 0,0962 | 0,0976 | 0,0990 | 0,1005 | 0,1020 | 0,1033 |
| 4 | 0,1213 | 0,1233 | 0,1253 | 0,1273 | 0,1292 | 0,1311 | 0,1330 | 0,1349 | 0,1369 | 0,1392 | 0,1409 |
| 5 | 0,1512 | 0,1537 | 0,1562 | 0,1586 | 0,1610 | 0,1634 | 0,1658 | 0,1682 | 0,1707 | 0,1736 | 0,1757 |

| The degree of opening of the pressure plate h, mm | Mass flow rate through the pressure plate Q, kg/s | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ΔP=1500, Pa | ΔP=1550, Pa | ΔP=1600, Pa | ΔP=1650, Pa | ΔP=1700, Pa | ΔP=1750, Pa | ΔP=1800, Pa | ΔP=1850, Pa | ΔP=1900, Pa | ΔP=1950, Pa | ΔP=2000, Pa |
| 6 | 0,1796 | 0,1826 | 0,1855 | 0,1884 | 0,1913 | 0,1941 | 0,1969 | 0,1998 | 0,2027 | 0,2061 | 0,2086 |
| 7 | 0,2086 | 0,2120 | 0,2154 | 0,2188 | 0,2221 | 0,2254 | 0,2287 | 0,2320 | 0,2355 | 0,2394 | 0,2423 |
| 8 | 0,2376 | 0,2415 | 0,2454 | 0,2492 | 0,2530 | 0,2568 | 0,2605 | 0,2642 | 0,2681 | 0,2728 | 0,2759 |
| 9 | 0,2698 | 0,2743 | 0,2787 | 0,2830 | 0,2873 | 0,2916 | 0,2958 | 0,3000 | 0,3043 | 0,3092 | 0,3130 |
| 10 | 0,2901 | 0,2949 | 0,2997 | 0,3043 | 0,3090 | 0,3135 | 0,3181 | 0,3226 | 0,3273 | 0,3327 | 0,3366 |
| 11 | 0,3197 | 0,3250 | 0,3303 | 0,3354 | 0,3405 | 0,3455 | 0,3505 | 0,3541 | 0,3605 | 0,3663 | 0,3708 |
| 12 | 0,3493 | 0,3551 | 0,3608 | 0,3664 | 0,3720 | 0,3775 | 0,3829 | 0,3883 | 0,3939 | 0,4002 | 0,4052 |
| 13 | 0,3710 | 0,3771 | 0,3832 | 0,3892 | 0,3951 | 0,4009 | 0,4067 | 0,4124 | 0,4184 | 0,4249 | 0,4301 |
| 14 | 0,4018 | 0,4084 | 0,4145 | 0,4215 | 0,4279 | 0,4342 | 0,4404 | 0,4466 | 0,4530 | 0,4604 | 0,4658 |
| 15 | 0,4298 | 0,4370 | 0,4440 | 0,4509 | 0,4577 | 0,4644 | 0,4711 | 0,4777 | 0,4845 | 0,4920 | 0,4979 |
| 16 | 0,4629 | 0,4705 | 0,4781 | 0,4855 | 0,4929 | 0,5001 | 0,5073 | 0,5144 | 0,5216 | 0,5291 | 0,5356 |
| 17 | 0,4733 | 0,4811 | 0,4888 | 0,4964 | 0,5039 | 0,5113 | 0,5186 | 0,5259 | 0,5332 | 0,5410 | 0,5478 |
| 18 | 0,5114 | 0,5198 | 0,5281 | 0,5363 | 0,5444 | 0,5524 | 0,5603 | 0,5681 | 0,5759 | 0,5842 | 0,5912 |
| 19 | 0,5228 | 0,5314 | 0,5399 | 0,5482 | 0,5565 | 0,5646 | 0,5726 | 0,5806 | 0,5885 | 0,5972 | 0,6047 |
| 20 | 0,5599 | 0,5691 | 0,5782 | 0,5872 | 0,5961 | 0,6048 | 0,6134 | 0,6220 | 0,6305 | 0,6393 | 0,6476 |

*Table 0.2 Mass flow rate of the vapor-air mixture through the half-open lid*

| The degree of opening of the pressure plate h, mm | Mass flow rate through the pressure plate Q, kg/s | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ΔP=1500, Pa | ΔP=1550, Pa | ΔP=1600, Pa | ΔP=1650, Pa | ΔP=1700, Pa | ΔP=1750, Pa | ΔP=1800, Pa | ΔP=1850, Pa | ΔP=1900, Pa | ΔP=1950, Pa | ΔP=2000, Pa |
| 1 | 0,0091 | 0,0092 | 0,0094 | 0,0095 | 0,0097 | 0,0098 | 0,0099 | 0,0101 | 0,0102 | 0,0103 | 0,0105 |
| 2 | 0,0256 | 0,0260 | 0,0264 | 0,0268 | 0,0273 | 0,0276 | 0,0280 | 0,0284 | 0,0288 | 0,0292 | 0,0296 |
| 3 | 0,0397 | 0,0404 | 0,0410 | 0,0417 | 0,0423 | 0,0429 | 0,0435 | 0,0441 | 0,0447 | 0,0453 | 0,0459 |
| 4 | 0,0554 | 0,0563 | 0,0572 | 0,0580 | 0,0589 | 0,0598 | 0,0606 | 0,0615 | 0,0623 | 0,0631 | 0,0639 |
| 5 | 0,0700 | 0,0711 | 0,0723 | 0,0734 | 0,0745 | 0,0756 | 0,0767 | 0,0777 | 0,0788 | 0,0798 | 0,0808 |
| 6 | 0,0836 | 0,0850 | 0,0863 | 0,0877 | 0,0890 | 0,0903 | 0,0916 | 0,0928 | 0,0941 | 0,0953 | 0,0965 |
| 7 | 0,0958 | 0,0974 | 0,0990 | 0,1005 | 0,1020 | 0,1035 | 0,1050 | 0,1064 | 0,1079 | 0,1093 | 0,1107 |
| 8 | 0,1039 | 0,1056 | 0,1073 | 0,1089 | 0,1106 | 0,1122 | 0,1138 | 0,1154 | 0,1169 | 0,1184 | 0,1199 |
| 9 | 0,1158 | 0,1177 | 0,1196 | 0,1214 | 0,1233 | 0,1250 | 0,1268 | 0,1286 | 0,1303 | 0,1320 | 0,1337 |
| 10 | 0,1406 | 0,1429 | 0,1452 | 0,1475 | 0,1497 | 0,1519 | 0,1540 | 0,1561 | 0,1582 | 0,1603 | 0,1623 |
| 11 | 0,1669 | 0,1697 | 0,1724 | 0,1751 | 0,1777 | 0,1803 | 0,1829 | 0,1854 | 0,1879 | 0,1903 | 0,1928 |
| 12 | 0,1771 | 0,1804 | 0,1832 | 0,1861 | 0,1889 | 0,1916 | 0,1943 | 0,1970 | 0,1996 | 0,2023 | 0,2048 |
| 13 | 0,1910 | 0,1944 | 0,1975 | 0,2005 | 0,2035 | 0,2065 | 0,2094 | 0,2123 | 0,2152 | 0,2180 | 0,2207 |
| 14 | 0,1963 | 0,1992 | 0,2024 | 0,2055 | 0,2087 | 0,2117 | 0,2148 | 0,2177 | 0,2206 | 0,2235 | 0,2264 |
| 15 | 0,2142 | 0,2177 | 0,2212 | 0,2246 | 0,2280 | 0,2313 | 0,2346 | 0,2378 | 0,2410 | 0,2442 | 0,2473 |
| 16 | 0,2197 | 0,2234 | 0,2269 | 0,2304 | 0,2339 | 0,2373 | 0,2407 | 0,2440 | 0,2473 | 0,2505 | 0,2537 |
| 17 | 0,2242 | 0,2284 | 0,2320 | 0,2356 | 0,2392 | 0,2426 | 0,2464 | 0,2503 | 0,2538 | 0,2576 | 0,2615 |
| 18 | 0,2288 | 0,2334 | 0,2371 | 0,2408 | 0,2444 | 0,2480 | 0,2521 | 0,2567 | 0,2603 | 0,2648 | 0,2694 |
| 19 | 0,2382 | 0,2423 | 0,2462 | 0,2500 | 0,2538 | 0,2575 | 0,2611 | 0,2647 | 0,2683 | 0,2718 | 0,2752 |
| 20 | 0,2658 | 0,2703 | 0,2746 | 0,2789 | 0,2831 | 0,2872 | 0,2913 | 0,2953 | 0,2992 | 0,3031 | 0,3070 |

# Appendix B

## Code for Arduino BMP280 and SI7021 sensors connected together

```
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_BMP280.h>

// SI7021 I2C address is 0x40(64) and BMP280 SPI
#define si7021Addr 0x40
#define PIN_CS 10
Adafruit_BMP280 bmp(PIN_CS);

void setup()
{
  Wire.begin();
  Serial.begin(9600);
  Wire.beginTransmission(si7021Addr);
  Wire.endTransmission();
  delay(300);
  if(!bmp.begin()) {
    Serial.println("BMP280 SENSOR ERROR");
    while(1);
  }
}

void loop()
```

```
{
  unsigned int data[2];

  Wire.beginTransmission(si7021Addr);
  //Send humidity measurement command
  Wire.write(0xF5);
  Wire.endTransmission();
  delay(500);

  // Request 2 bytes of data
  Wire.requestFrom(si7021Addr, 2);
  // Read 2 bytes of data to get humidity
  if(Wire.available() == 2)
  {
    data[0] = Wire.read();
    data[1] = Wire.read();
  }

  // Convert the data
  float humidity  = ((data[0] * 256.0) + data[1]);
  humidity = ((125 * humidity) / 65536.0) - 6;

  Wire.beginTransmission(si7021Addr);
  // Send temperature measurement command
  Wire.write(0xF3);
  Wire.endTransmission();
  delay(500);

  // Request 2 bytes of data
  Wire.requestFrom(si7021Addr, 2);

  // Read 2 bytes of data for temperature
  if(Wire.available() == 2)
  {
    data[0] = Wire.read();
    data[1] = Wire.read();
```

```
    }

    // Convert the data
    float temp  = ((data[0] * 256.0) + data[1]);
    float celsTemp = ((175.72 * temp) / 65536.0) - 46.85;
    float OverallTemp = (celsTemp + bmp.readTemperature()) / 2;

    // Output data to serial monitor
    Serial.print("Влажность : ");
    Serial.print(humidity);
    Serial.println(" % RH");

    Serial.print("Температура SI7021 : ");
    Serial.print(celsTemp);
    Serial.println(" C");

    Serial.print(F("Температура BMP280 = "));
    Serial.print(bmp.readTemperature());
    Serial.println(" C");

    Serial.print("Средняя температура : ");
    Serial.print(OverallTemp);
    Serial.println(" C");

    Serial.print(F("Давление = "));
    Serial.print(bmp.readPressure());
    Serial.println(" Па");

    Serial.println();

    delay(2000);
}
```

# Appendix C

## Sensor readings during the experiment

*Table 0.3  The experimental fata*

| Test № | T temperature at the beginning, ˚C | ρ saturated steam at the beginning, $g/m^3$ | T temperature at the end, ˚C | ρ saturated steam at the end, $g/m^3$ | ρ unsaturated steam, $g/m^3$ | φ, % | m saturated steam at the beginning, g | m steam at the end, g | Δm, g |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 50,0 | 83,0 | 45,0 | 67,1 | 47,0 | 0,7 | 4,4 | 2,5 | 1,9 |
| 2 | 50,0 | 83,0 | 45,0 | 67,1 | 43,6 | 0,7 | 4,4 | 2,3 | 2,1 |

| Test № | T temperature at the beginning, ˚C | ρ saturated steam at the beginning, $g/m^3$ | T temperature at the end, ˚C | ρ saturated steam at the end, $g/m^3$ | ρ unsaturated steam, $g/m^3$ | φ, % | m saturated steam at the beginning, g | m steam at the end, g | Δm, g |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3 | 50,0 | 83,0 | 45,0 | 67,1 | 40,3 | 0,6 | 4,4 | 2,1 | 2,3 |
| 4 | 50,0 | 83,0 | 45,0 | 67,1 | 43,6 | 0,7 | 4,4 | 2,3 | 2,1 |
| 5 | 50,0 | 83,0 | 45,0 | 67,1 | 38,9 | 0,6 | 4,4 | 2,1 | 2,3 |
| 6 | 50,0 | 83,0 | 45,0 | 67,1 | 33,6 | 0,5 | 4,4 | 1,8 | 2,6 |
| 7 | 55,0 | 106,5 | 45,0 | 67,1 | 43,6 | 0,7 | 5,7 | 2,3 | 3,3 |
| 8 | 60,0 | 130,0 | 50,0 | 83,0 | 50,6 | 0,6 | 6,9 | 2,7 | 4,2 |
| 9 | 60,0 | 130,0 | 50,0 | 83,0 | 53,1 | 0,6 | 6,9 | 2,8 | 4,1 |
| 10 | 60,0 | 130,0 | 50,0 | 83,0 | 56,4 | 0,7 | 6,9 | 3,0 | 3,9 |
| 11 | 60,0 | 130,0 | 50,0 | 83,0 | 54,0 | 0,7 | 6,9 | 2,9 | 4,0 |
| 12 | 60,0 | 130,0 | 50,0 | 83,0 | 50,6 | 0,6 | 6,9 | 2,7 | 4,2 |
| 13 | 60,0 | 130,0 | 50,0 | 83,0 | 53,1 | 0,6 | 6,9 | 2,8 | 4,1 |
| 14 | 60,0 | 130,0 | 50,0 | 83,0 | 51,5 | 0,6 | 6,9 | 2,7 | 4,2 |

| Test № | T temperature at the beginning, ˚C | ρ saturated steam at the beginning, g/m$^3$ | T temperature at the end, ˚C | ρ saturated steam at the end, g/m$^3$ | ρ unsaturated steam, g/m$^3$ | φ, % | m saturated steam at the beginning, g | m steam at the end, g | Δm, g |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 15 | 60,0 | 130,0 | 30,0 | 30,3 | 18,2 | 0,6 | 6,9 | 1,0 | 5,9 |
| Σ | | | | | | | | | 51,3 |

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# Abbreviations

| | |
|---|---|
| O&OP | Oil and Oil Products |
| CBV | Combined Breathing Valve |
| VST | Vertical Steel Tank |
| GS | Gas Space |
| HST | Horizontal Steel Tank |
| AFS | Automobile Filling Station |
| LFH | Light Fraction Of Hydrocarbons |
| API | American Petroleum Institute |