Theoretical Justification of Experimental Investigation of
Gravity-Capillary Method for Gas-Liquid Mixtures Intake

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Abstract. The process of interaction of an adaptive spatial permeable capillary phase separator with a gas-liquid interface in a vessel in the gravitational field of the Earth was investigated. The existence of a natural comprehensive compression force acting on a capillary phase separator was theoretically justified and experimentally confirmed. This force is compensated by the structure rigidity in classical devices. It was shown that the volume of the capillary phase separator covered by a gas was decreased in a compliant structure under the action of this force in the liquid outflow process. Due to this, it is possible to maintain a total pressure differential for the capillary phase separator at low flow rates of the liquid below a capillary differential defined by the well-known Laplace’s formula. This effect allows reducing a remaining portion of a liquid in a vessel and expanding the practical application area of capillary phase separators including intake systems operating under conditions of elevated accelerations and temperatures.

1. Introduction

Ensuring the separation of gas and liquid phases in vessels of complex configuration during the liquid intake process in technical systems of various purposes in the case of external dynamic influences is a complex applied scientific and technical problem. As a rule, mechanical, inertial, capillary intake devices are used to solve this problem. However, the use of the latter is complicated, in particular, by the presence of linear overloads significantly reducing the efficiency of their operation.

An adaptive gravity-capillary device (hereinafter – the adaptive device) implementing a new liquid intake method is proposed to extend the range of use of traditional capillary intake devices.

The purpose of the work is the theoretical justification and experimental confirmation of the possibility of implementing the proposed method.

The liquid intake device is placed in a vessel so that the liquid medium in the intake process enters a feed line through a microporous material, which is a capillary phase separator.

It is known that there are two limiting modes during the operation of the capillary phase separator, which are a separating mode and a retaining mode. When changing the position of a gas-liquid interface, the structure is subjected to an external pressure differential which is compensated by the adaptive device.
interface (hereinafter – the surface $\Sigma$) caused by a decrease in the liquid volume and/or a direction of a total overload vector there is a situation, in which one portion of the volume of the capillary intake device is immersed in the liquid, and the other portion is located above the surface $\Sigma$ in the gas phase.

In this case, a hydraulic barrier (the capillary phase separator filled with the liquid) appears, and the phase separator operates both in the separating mode and in the liquid medium retention mode, thus preventing the gas penetration into an internal volume of the capillary intake device and, therefore, into the feed line of the liquid intake system. An algebraic inequality determining the existence of the hydraulic barrier is written as follows [1, 2]:

$$CRC \geq \Phi(h, \Delta P_{\text{sum}}, n),$$  \hspace{1cm} (1)

where CRC = $4\sigma \cos \theta / d_{eq}$, CRC – capillary retention capacity of the capillary phase separator, $\sigma$ – specific free energy of the surface $\Sigma$ (surface tension coefficient of the liquid), $\theta$ – limiting wetting angle, $d_{eq}$ – equivalent diameter of the capillary phase separator, $\Phi = \rho_{\text{liq}} gh + \Delta P_{\text{sum}}$, $\rho_{\text{liq}}$ – liquid density, $n$ – modulus of the total overload vector $n_{\Sigma}$, $g$ – gravitational acceleration, $h$ – height of the capillary intake device above the surface $\Sigma$ in the gas phase region in the direction of the action of the vector $n_{\Sigma}$, $\Delta P_{\text{sum}}$ – total losses of liquid pressure of the capillary phase separator.

$$\Delta P_{\text{sum}} = \Delta P_{\text{CPS}} + \Delta P_{\text{HR}} + \Delta P_{\text{dyn}} + \Delta P_{\text{vibr}} + \Delta P_{\text{puls}}$$

in the expression (1), where $\Delta P_{\text{CPS}}$ – hydraulic pressure losses arising from the movement of the liquid through the capillary phase separator; $\Delta P_{\text{HR}}$ – hydraulic pressure losses during the movement of the liquid inside the capillary phase separator; $\Delta P_{\text{dyn}}$ – dynamic pressure losses in the feed line due to a dynamic pressure of the liquid; $\Delta P_{\text{vibr}}$ – pressure losses arising from the vibration of the structure of the capillary intake device; $\Delta P_{\text{puls}}$ – pressure losses caused by liquid pulsations in the hydraulic system.

The retention mode of the capillary phase separator is violated if CRC < $\Phi$ or $h > h_{\text{lim}}$, where $h_{\text{lim}}$ – height of a hydrostatic column of the liquid inside the capillary intake device; the column is held by the surface tension forces of the capillary phase separator. At this time point, the capillary phase separator goes into the separating mode of operation.

Figure 1, a illustrates the separating and retaining modes of operation of the capillary phase separator. Figure 1, b shows the separating mode of operation of the capillary phase separator and the violation of the integrity of the hydraulic barrier (the beginning of filling an internal volume of the capillary intake device with the gas phase is conventionally displayed). Contour arrows in both figures indicate the direction of liquid movement; solid arrows indicate the presence of an external pressure of the gas phase. The following designations are used: «go» and «do» correspond to the gas and liquid phases; $t_1$ and $t_2$ relate to different times of the dynamic process of liquid intake from the vessel, $t_2 > t_1$.

It is required to provide the inequality (1) to improve the performance characteristics of the capillary intake device under conditions of a variable capillary retention capacity and changing physical properties of the liquid medium. For this, it is necessary to solve a function minimization problem $\Phi$. One of approaches for obtaining the minimum value of $\Phi$ is to use the proposed gravity-capillary method.

2. Theoretical basis of gravity-capillary interactions of surfaces

A distinctive feature of the gravity-capillary method of intake of the liquid component of a homogeneous mixture with gas inclusions is the following. In the process of liquid intake, the volume of the capillary intake device is reduced so that its height $h_c$ above the surface $\Sigma$ in the vessel in the direction of the action of the vector $n_{\Sigma}$ is less than the height of the hydrostatic column held by surface tension forces of the capillary phase separator: $h_{\text{lim}}$: $h_c < h_{\text{lim}}$. For this, an unbalanced natural
comprehensive compression force is used in the process of liquid intake in the case of appearing a pressure differential between an internal cavity of the capillary intake device located above the surface \( \Sigma \) and a gas cavity of the vessel; this force is occurred when the system of inequalities is fulfilled (the case of reducing the volume of the capillary intake device in the direction of the vector \( \mathbf{n} \) is considered without loss of generality in accordance with Figure 2) [3]:

\[
\begin{cases}
    m_{RM} ng + \rho_{liq} ng (x_z(Q) - x) S_{ef} - \tilde{c}_{CPS} (x_z(Q) S_{ef} - \Delta V(x)) \geq 0, \\
    \text{CRC}(T) \geq \rho_{liq} ng (x_z(Q) - x) + \Delta p_{\text{sum}},
\end{cases}
\]

(2)

where \( m_{RM} \) – reduced mass of the moving part of the structure of the capillary intake device, \( x \) – value of the movement of the structure of the capillary intake device in the process of volume reduction relative to an initial state, \( x \in [0; x_{\text{max}}] \), \( x_{\text{max}} \) – movement of the structure of the capillary intake device in the case of the maximum volume reduction, \( Q \) – volume flow rate of the liquid from the vessel, \( x_z \) – movement of the surface \( \Sigma \) in the vessel relative to an initial position of the structure of the capillary intake device, \( S_{ef} \) – effective area of the of the capillary intake device in the direction of the vector \( \mathbf{n} \) (area of a projection of the structure of the capillary intake device; the projection is orthogonal to the vector \( \mathbf{n} \) and located above the surface \( \Sigma \) in the gas phase region), \( \tilde{c}_{CPS} = c_{CPS}/S_{ef} \) – reduced rigidity coefficient of the structure of the capillary intake device, \( c_{CPS} \) – rigidity coefficient, \( \Delta V(x) \) – volume of the capillary intake device located above the surface \( \Sigma \) in the gas phase region, \( T \) – liquid temperature.

Decreasing the remaining portion of the liquid in the vessel is achieved by reducing the volume of the capillary intake device in the process of intake of the liquid medium by using an unbalanced natural comprehensive compression force occurring and impacting on the structure of the capillary intake device in the case of appearing a pressure differential between an internal cavity of the capillary intake device located above the surface \( \Sigma \) and a gas cavity of the vessel.

Let us estimate conditions determining the possibility of implementing the gravity-capillary method. A fixed coordinate system \( OX_s \), \( x \in [0; x_{\text{max}}] \) is introduced. The system is presented in Figure 2. A coordinate \( h_s \), which is the current value of the height of the retained liquid column, is determined, \( h_s \geq 0 \); this coordinate is measured from a moving part of the structure of the capillary intake device. Figure 2 indicates: \( H_{\text{max}} \) – height of the structure of the capillary intake device in the initial state, \( H_{\text{max}} \) – height of the structure of the capillary intake device.
The system of inequalities (2) is obtained. The projection of an equation of movement of the moving part of the structure of the capillary intake device onto the axis $OX$ is written neglecting a friction force that occurs during the movement of the liquid mass inside the capillary intake device: 

$$m_{RM} \frac{d^2 x}{dt^2} = p_g S_d + m_{RM} \rho_{liq} S_d - F_{CPS},$$

where $t$ - time, $p_g$ - gas pressure, $p_{liq}^A$ - liquid pressure in the point $A$, $F_{CPS}$ - resistance force due to the rigidity of the structure of the capillary intake device. It follows from this equation that the decrease in the volume of the capillary intake device occurs only if the algebraic inequality

$$m_{RM} \rho_{liq} S_d - F_{CPS} \geq 0,$$

where

$$p_g S_d + m_{RM} \rho_{liq} S_d - F_{CPS} \geq 0.$$ 

According to the Galileo-Torricelli principle, a liquid pressure at the point $A$ is determined by a gas phase pressure $p_g$ and a liquid column height $h$: 

$$p_{liq}^A = p_g - \rho_{liq} \rho_{liq}^A h = p_g - \rho_{liq} (x_2 - x).$$

One can get the following expression inserting this formula into the algebraic inequality:

$$m_{RM} \rho_{liq}^A (x_2 - x) S_d - F_{CPS} \geq 0.$$ 

The modulus of the resistance force $F_{CPS}$ is determined by the formula

$$F_{CPS}(x) = \bar{c}_{CPS} \left( x_2 S_d - \Delta V(x) \right).$$

In general case, a position of the surface $\Sigma$ in the vessel is determined by the volume flow rate of the liquid $Q$: $x_2 = x_2(Q)$. One finally gets after performing the transformations:

$$m_{RM} \rho_{liq}^A (x_2(Q) - x) S_d - \bar{c}_{CPS} (x_2(Q) S_d - \Delta V(x)) \geq 0.$$ 

It should be noted that the natural comprehensive compression force appears only if the retention capacity of the hydraulic barrier is not violated in the process of reducing the volume of the capillary intake device, i.e. the condition (1) is ensured:

$$CRC \geq \rho_{liq}^A (x_2(Q) - x) + \Delta \rho_{sum}.$$ 

The system of inequalities (2) determines the impact of the unbalanced natural comprehensive compression force on a decrease in the volume of the capillary intake device. Thus, using the proposed method, a total remaining portion of the liquid depends on geometric characteristics of the capillary intake device in the vessel and can be reduced (for identical values of the capillary retention capacity, fuel flow rate, initial volume of the capillary intake device) by the difference of the liquid volumes (inside the capillary intake device) in the initial and final state of the capillary intake device and by the difference between the liquid volume in the vessel (outside the capillary intake device) corresponding to the capillary retention capacity in the initial state of the capillary intake device and the minimum volume of the liquid in the vessel corresponding to the minimum structural volume of the capillary intake device in the final state.
A structure of a complex nonstationary mathematical model based on fundamental laws of continuum mechanics is used for the computer modeling of dynamic processes during the operation of the adaptive device as a part of a liquid intake system. This structure includes:
- one-dimensional nonstationary model of the change in thermodynamic parameters of a real gas in a variable free volume of a gas-liquid cavity of a vessel [4, 5];
- three-dimensional nonstationary model of movement of a homogeneous liquid medium through a deformed capillary phase separator in a variable liquid volume of the gas-liquid cavity of the vessel;
- mechanical model of a translational movement of the moving part of the device structure under the action of the force of natural and/or artificial gravity, as well as surface forces from interaction with the gas and liquid phases;
- three-dimensional nonstationary asymptotic model of surface and volume effects of the interaction of a homogeneous liquid medium, the gas phase and the material of the capillary phase separator in a deformable side surface of the device [6-8].

3. Experimental installation
The adaptive device made in the form of a permeable bellows is proposed as a prototype of the structure of the capillary intake device operating according to the described gravity-capillary method. A side surface of the liquid intake device has a mechanical compliance along the axis of symmetry of the capillary phase separator.

The research of dynamic characteristics of the adaptive device was made to confirm the adequacy of the method; and these dynamic characteristics were compared with similar physical parameters of the capillary intake device of a rigid structure (hereinafter – a rigid device). Figure 3 shows the experimental installation consisting of a polymeric transparent vessel, in which a metal mount pillar is placed; the prototype of the adaptive device is fixed in the mount pillar.

A liquid intake line 2 is a flexible silicone transparent hose with the ability to visually monitor the continuity of the liquid flow. The hose is connected to an outlet pipe located in a lower part of the adaptive device. The moving part of the device structure prototype 5 has a guide 4 made in the form of steel wire, which can move freely in special machining attachments, thus providing a mechanical flexibility of the adaptive device in the direction of the gravitational acceleration vector. Water is used as a working fluid. Measurement of its volumetric flow rate was performed by post-processing the recorded video image of the experiment with the use of the calibrated vessel.

![Figure 3. Appearance of the experimental installation: 1 - clamp, 2 – liquid intake line, 3 – calibrating scale, 4 - guide, 5 – prototype of the device design, 6 – mount pillar, 7 – vessel with a liquid (water)](image)

4. Discussion of research results
Figure 4, a and b shows freeze frames of the dynamic process of the liquid intake from the vessel of the experimental installation with the use of the rigid device and one of the adaptive device prototypes respectively.
The number of the freeze frame corresponds to the volume of the liquid taken from the vessel; the volume is in liters. So, the freeze frame № 0 displays the vessel of the experimental installation in a filled state; the freeze frame № 1 shows that 1 liter of the liquid is taken from the vessel; 2 liters of the liquid are taken in the freeze frame № 2, etc. An exception is made by the freeze frames № 12 and 13 in Figure 4, a, as well as the freeze frame № 13 in Figure 4, b. The freeze frame № 12 presented in Figure 4, a, corresponds to the beginning of the penetration of the gas phase in the rigid device through the capillary phase separator, but 11.5 liters of the liquid are taken from the vessel. Further, the gas-liquid mixture comes to the liquid intake line due to the destruction of the hydraulic barrier (freeze frame № 13).

The freeze frame № 13 presented in Figure 4, b also corresponds to a situation of the gas entering the adaptive device, a structural volume of which slightly increases. The freeze frame № 3 (it is not shown, since it does not differ from the freeze frame № 3) presents the beginning of the process of movement of the structure of the adaptive device. Table shows the correspondence of the freeze frame number to the time value of the dynamic process.

**Table 1.** Values of the time of the dynamic process for freeze frames during the liquid intake by the rigid device and the adaptive device

| Freeze frame number | Time, s  | Freeze frame number | Time, s |
|---------------------|---------|---------------------|---------|
| 0                   | 0/0     | 6                   | 163/179 |
| 1                   | 26/28   | 7                   | 192/212 |
| 2                   | 52/58   | 8                   | 221/244 |
| 3'                  | 187.784 | 9                   | 251/277 |
| 3                   | 79/88   | 10                  | 282/311 |
| 4                   | 106/118 | 11                  | 313/345 |
| 5                   | 134/149 | 12                  | 350/381 |

Note. The numerator shows values for the rigid device; the denominator specifies values for the adaptive device.

It is noted that the rigid structure of the device is obtained by limiting the degree of freedom of the adaptive device along its axis of symmetry by fixing the moving part in the machining attachments.

Conditions of the experiment: an ambient temperature is 20°C, an atmospheric pressure is 99.1 kPa, \(Q = 31.3\) ml/s, \(n = 1\). Physical characteristics of the liquid: \(\rho_{\text{liq}} = 997.8\) kg/m³, \(\sigma = 78.9\) mN/m; the maximum possible volume of the taken liquid medium determined by structural features of the experimental installation is 12 l. Structural and physical characteristics of the capillary phase
separator: \(d_{eq} = 303 \mu m\), CRC=963 Pa (calculated without loss of generality at \(\Delta p_{sum} = 0\), \(\theta = 0^\circ\)), \(h_{lim} = 98.3\ mm\).

Functions \(\Phi^R\) and \(\Phi^A\) were plotted according to the analysis of freeze frames (Figures 4, a and b). \(\Phi^R(t) = \Phi(h^R(t),0,1)\) and \(\Phi^A(t) = \Phi(h^A(t),0,1)\) for these functions at \(\Delta p_{sum} = 0\) and \(n=1\) (Figure 5), where \(h^R(t)\), \(h^A(t)\) – height of the retained liquid column of the rigid device and the adaptive device. Numbers of the corresponding freeze frames shown in Figures 4, a and b are designated in graphs by dots.

It was found out that the rigid device started to pass the gas phase through the capillary phase separator at the time moment \(t = 350\ s\) from the experiment beginning (point 12 of the curve \(\Phi^R(t)\)) due to the destruction of the hydraulic barrier (Figure 4, a, the freeze frame № 12). In this case, the graphs CRC\((t)\) and \(\Phi^R(t)\) intersect at the point 12 with coordinates (350; 963); the point corresponds to the expression \(h^R(t) = h_{lim}\), and the inequality (1) is not satisfied at \(t > 350\ s\). At the same time, the untaken volume of the liquid in the vessel of the experimental installation is 0.5 l (4.2% of the maximum possible volume of the taken liquid medium). In the case of the use of the adaptive device, the point 12 of the curve \(\Phi^A(t)\) (see Figure 5) corresponds to almost complete intake of the maximum possible volume of the taken liquid medium (~ 12 l).

The process of movement of the adaptive device by the natural comprehensive compression force starts at the time moment \(t \approx 87.8\ s\) from the beginning of the experiment at the point 3’ of the curve \(\Phi^A(t)\); the freeze frame № 3’ in Figure 4, b (not shown) corresponds to the process. At each time moment \(t > 87.8\ s\), points of the graph of the function \(\Phi^A\) are located below the curve \(\Phi^R(t)\), i.e. \(\Phi^A(t) < \Phi^R(t)\ \forall t > 87.8\ s\). It indicates that the right-hand side of the inequality (1) changes due to the correction (reduction) of the volume of the structure of the capillary intake device. In this case, the existence of a hydraulic barrier is determined not by the formula (1), but by the second inequality of the system (2).

It should be mentioned that the process of disruption of the hydraulic barrier of the adaptive device (Figure 4, b, the freeze frame № 12) starts after the completion of the intake of the maximum possible volume of the liquid (point 12 of the curve \(\Phi^A(t)\)). In contrast to the rigid structure of the device, this is due to the consummation of the liquid medium located inside the maximum compressed capillary intake device.

The relative coefficient of adaptability \(k_{CPS}^{AR} = 2 - \Phi^A(t^A)/\Phi^R(t^R)\) is determined for the given class of the capillary phase separator \(CPS\{\sigma, \theta, d_{eq}\}\) induced by parameters \(\sigma, \theta,\) and \(d_{eq}\), where \(t^A\) and \(t^R\) – the time moment, for which the hydraulic barrier of the rigid device and the adaptive device is disrupted.

It should be mentioned that \(k_{CPS}^{AR} = 1\) in the \(CPS\{\sigma, \theta, d_{eq}\}\) class, wherein \(k_{CPS}^{AR} = 1\) corresponds to the rigid device, and \(k_{CPS}^{AR} = 2\) relates to the adaptive device; wherein the adaptive phase have the capillary phase separator with a high degree of compliance. The equality \(\Phi^R(t^R) = CRC\) is fulfilled in the point 12 of the curve \(\Phi^R(t)\), so \(k_{CPS}^{AR} = 2 - \Phi^A(t^A)/CRC\). It should be noted that the function minimization problem \(\Phi\) from the inequality (1) leads to an equivalent formulation \(k_{CPS}^{AR} \rightarrow \max\), as \(\left(k_{CPS}^{AR}\right)_{\max} = \lim_{\Phi^A \rightarrow 0} k_{CPS}^{AR}\).
As $k_{CPS}^{AR}$ is different from one (approximately 1.72) for the considered adaptive device, the constant (time independent) function $M^A$ is introduced; the inequality $CRC \geq M^A > \Phi^A$ is fulfilled for the function $M^A$ at $\forall t \in [0; t^A]$. On the one hand, this relation and Figure 5 show that there is a certain time moment $\bar{t} \in [t_{in}; t^A]$ ($t_{in}$ - time of the beginning of movement of the moving part of the structure of the adaptive device) during the function minimization, and the system is correct: $CRC > M^A > \Phi^A \forall t \in [t_{in}; \bar{t}]$, $CRC \geq \Phi^A \geq M^A > \Phi^A \forall t \in [\bar{t}; t^A]$. These relations define the function $\Phi^A$ as the desired local optimal value $\Phi$ when solving the problem $\Phi \rightarrow \min$. Therefore, the classical inequality (1) can be specified and presented in the form $M^A > \Phi^A$ for the adaptive device. On the other hand, at $k_{CPS}^{AR} \in (1; 2]$, the capillary intake device automatically implements the safety factor of the capillary retention capacity of the adaptive device $k_{SF}^A \in \mathbb{R}$, $k_{SF}^A > 1$ determined by the formula $k_{SF}^A = CRC/M^A$. $k_{SF}^A$ is 2.75 at $M^A(t) = 350$ Pa for the considered structure of the adaptive device. In fact, this may mean that instead of the current capillary phase separator it is possible to use such a phase separator, for which $d_{eq}$ is five times as much during maintaining the parameters $\sigma, \theta$, and elastic characteristics.

![Graph](image)

**Figure 5.** Dependence of operational characteristics of the rigid device and the adaptive device from the time $t$.

### 5. Practical use of the gravity-capillary method

The proposed method of the liquid intake can be used in engineering and technical systems of various purposes: fuel systems of spacecrafts and aircrafts [9], systems for intake of liquids from vessels of a complex spatial configuration, systems for intake of chemically hazardous and radioactive liquids and gas-liquid mixtures, etc.

Figure 6 shows the case of the dynamic process of liquid transport from the vessel through the capillary phase separator for the bottom horizontal position of the adaptive device. For the freeze frame matrix, the surface $\Sigma$ is orthogonal to the gravitational acceleration vector. It should be noted that the use of the natural comprehensive compression force allows minimizing remaining portions of the liquid to ensure continuity and flow filtration. The freeze frame, which is located in the third row
and the third column, shows the moment of gas penetration into the liquid intake line (one can see a gas bubble in the silicone transparent hose) – the final stage of the process. This example demonstrates the independence of the natural comprehensive compression force from the location of the adaptive device in the vessel.

![Horizontal arrangement of the adaptive device in the vessel.](image)

**Figure 6.** Horizontal arrangement of the adaptive device in the vessel.

6. **Conclusions**

It was shown that it was possible in principle to create the capillary intake device that adapted to the influence of external factors due to the correction (reduction) of geometric dimensions. It was experimentally confirmed that such correction could be achieved in the adaptive (compliant) capillary intake device due to the natural comprehensive compression force acting on its structure in the process of intake of the liquid from the vessel from the moment of the appearance of the capillary hydraulic barrier. Methodological foundations and the structure of the complex mathematical model of physical processes of the liquid intake from the vessel through the variable-geometry capillary intake device were presented. The results of the research allow expanding the field of use of the capillary intake device for systems operating under conditions of influencing factors that are uncharacteristic for the capillary intake device.

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