Vapor Recovery Unit of Gasoline from the Tanks of Filling Stations with Gas-Dynamic Cooling

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Abstract. This study presents a gasoline vapor recovery unit of a gas station, which is based on a vortex tube and a shell-and-tube heat exchanger. The calculation of system is made and technological scheme is presented. Shown effectiveness of the device and drawn conclusions about its rationality

1. Introduction

The evaporation of gasoline from underground tanks is undesirable both economically and ecologically. Part of this evaporation comes from a “strong breathing” [1-2].

The “strong breathing” of a reservoir is a process of vapor-aerial mixture (VAM) displacement during filling operations. VAM in tank is compressed by incoming gasoline until pressure reaches operating pressure of breathing valve. That is the point of “exhale”. If VAM pressure reaches some limit, for example 2000 Pa, the tank can rupture [2-4].

A number of recuperation system has been studied recently: condensation by cooling [5], adsorption [6-7], absorption [8] and membrane technologies [9]. This study proposes vapor cooling recuperation system to reduce “strong breathing” evaporation losses.

Systems with active gas-dynamic based on Ranque-Hilsch vortex tube effect have acceptable specific effectiveness. Such systems divide inlet flow into two flows: cold flow and hot flow [10].

Vortex tubes in recuperation systems have several advantages: quick access to operation mode, absence of dangerous coolants, compactness, few moving parts. The simplicity of the design determines its reliability, additionally the system allows for several processes simultaneously (heating, cooling and phase separation).

Figure 1 presents the studied system. In order to condense vapor from an underground tank 1, the vortex tube 2 must be combined with a heat exchanger 3, which will be installed on the breathing valve 4 through the flanges 8. Heat is removed by blowing the heat exchanger tube system with cold flow generated in the vortex tube, into which air is supplied at ambient temperature from the compressor 10. Passing through the shell space in the heat exchanger, the cold flow goes back into the atmosphere.

In case of emergency, for example, blockage of the heat exchanger tubes, two pressure sensors 9 and bypasses 6 are installed to bypass the heat exchanger. If the outlet sensor reads below the heat exchanger inlet sensor, the telemetry system recognizes this situation as blockage and opens heat exchanger bypass 6 and the vortex tube bypass 7 while closing outlet hot flow valve 11. Overpressure
is released through the breather valve and heat exchanger heated to eliminate icing. In this mode system works until the pressure sensor readings are equal.

2. Goals and objectives
The main goal of the study is to analyze vortex tube (figure 1) vapor recuperation system efficiency. The objectives were to experimentally determine vortex tube temperature efficiency; calculate heat exchanger and calculate phase transition of vapor system.

![Figure 1. Recuperation system.](image)

1- underground horizontal tank; 2- vortex tube; 3-heat exchanger; 4- breathing valve; 5-telemetry and automation system; 6,7- bypasses; 8-flanges; 9- pressure sensor; 10-compressor; 11-electric valve; CF-cold flow; HF-hot flow.

3. Materials and methods

3.1. Vortex tube
Temperature efficiency of vortex tube was studied on vortex installation of Oil & Gas and petrochemical industry department of FEFU [11]. Figure 2 represents studied countercurrent vortex tube. Parameters of the system were: inlet air to cold air pressure ratio $\pi = 5$ and $\pi = 7$; inlet air mass flow 32 kg/h and 62 kg/h accordingly; ambient air temperature 294.4 K.

3.2. Heat exchanger calculation
Since there is a known mass of hydrocarbons that must be condensed over a period of time [12], the task is to determine the parameters of the heat exchanger.

In this study shell-and-tube heat exchanger is proposed to use in the system. Heat carriers are: cooling air in the shell and VAM in tubes.

There are many different models for calculating heat exchangers, including modifications of standard models [13-19]. The mathematical model of the heat exchanger includes the basic equation of heat transfer, the equation of conservation of mass and heat balance, the criterial equations of fluid properties. Since the heat transfer in the radial direction is small, it is possible to make a number of assumptions [16]:
- One dimensional flow, ignoring flow diffusion;
- Radial direction heat transfer is negligible.

To calculate the thermal characteristics of the heat exchanger, the UniSim Design R451 program was used [20-21]. The geometric parameters of the heat exchanger were set according to the size of
The breathing valve of the gas station tank. For this reason, the diameter of the shell of the heat exchanger was chosen to be 50 mm. The heat exchanger was calculated using the Steady State Rating model. Steady State Rating model allows to calculate the duty of the heat exchanger through its geometric parameters [20-21].

3.3. Hydrocarbon condensation calculation

The Gasoline vapor predominantly consists of light hydrocarbons with carbon chain length of C2-C7, including aromatic hydrocarbons (HC) such as benzene, toluene [22].

Table 1 shows fraction composition of VAM examined in this study. It consists of 34.406% HC and 65.594% air [23]. The fraction of condensed HC was calculated via Unisim Design R451 with subprogram “Peng-Robinson equation of state” which is widely used to describe HC state, especially for alkanes and their mixtures. Figure 3 shows technological scheme in UniSim Design.

Figure 2. Experimental countercurrent vortex tube.

Figure 3. Calculation scheme for determining the efficiency of condensation of HC.
The calculations were made with assumption that 1 m\(^3\) of gasoline displace about 0.88 kg of VAM [12]. In this work loading of 10 m\(^3\) of gasoline is studied, so the gasoline displaces 8.8 kg of VAM. According to table 1, such mixture contains 2.94 kg of HC.

**Table 1.** Fraction composition of VAM.

| Component   | Volume fraction, % | Mass fraction, % |
|-------------|--------------------|------------------|
| Methane     | 0.0699             | 0.0315           |
| Ethane      | 0.3677             | 0.3110           |
| Ethylene    | 0.0279             | 0.0220           |
| Propane     | 1.5029             | 1.8625           |
| Propylene   | 0.0055             | 0.0065           |
| Butane      | 4.5792             | 7.4790           |
| Isobutane   | 3.5154             | 5.7415           |
| Pentane     | 4.3723             | 8.8650           |
| Hexane      | 2.7725             | 6.7145           |
| Heptane     | 0.3802             | 1.0705           |
| Octane      | 0.0051             | 0.0165           |
| Nonane      | 0.0010             | 0.0035           |
| Benzene     | 0.5228             | 1.1475           |
| Toluene     | 0.0286             | 0.0740           |
| Ethylbenzene| 0.0191             | 0.0570           |
| Xylene      | 0.0012             | 0.0035           |
| Air         | 81.829             | 66.594           |

VAM molar mass is \(M = 35.59\) kg/kmole; density \(\rho = 1.49\) kg/m\(^3\); specific heat capacity \(c_p = 1390.32\) J/(kg·K).

4. Results and discussion

4.1. Vortex tube experimental data
Figures 4 and 5 show the characteristics of the studied countercurrent vortex tube. Figure 4 shows temperature difference between the cold flow as a function of cold flow fraction. Figure 5 shows cooling capacity as a function of cold flow fraction.

![Figure 4](attachment:image.png)

**Figure 4.** Cold flow temperature difference as a function of cold flow ratio at the pressure ratio of \(\pi = 5\) and \(\pi = 7\).
The following parameters were achieved: the maximum temperature difference of the investigated vortex tube for cold flow 29.4 K at the cold flow fraction of $\mu = 0.55$ and pressure ratio of $\pi = 5$; the maximum temperature difference of the cold flow 32.7 K at the cold flow fraction of $\mu = 0.42$ and pressure ratio of $\pi = 7$ (figure 4). The maximum cooling capacity is 603.5 kJ/h at the cold flow fraction of $\mu = 0.65$ and $\pi = 5$; the maximum cooling capacity is 1068 kJ/h at the cold flow fraction of $\mu = 0.66$ and $\pi = 7$ (figure 5). The obtained data were used for further mathematical modeling in UniSim Design R451.

4.2. Heat exchanger design and parameters
The following calculation results were obtained for the heat exchanger in UniSim Design R451: shell diameter 50 mm, length of the shell and tubes 1.5 meters, number of tubes per shell 19 pieces, tube pitch 1 mm, baffle spacing 50 mm, baffle cut 20%. The heat exchange area of this construction was 0.716 $m^2$. The heat transfer coefficient of the heat exchanger during the operation of the vortex tube at the pressure ratio of $\pi = 7$ and maximum cooling capacity was $UA = 193.5 \text{kJ/(h} \cdot \text{K)}$. The heat transfer coefficient of the heat exchanger during the operation of the vortex tube at the pressure ratio of $\pi = 5$ and maximum cooling capacity was $UA = 169.5 \text{kJ/(h} \cdot \text{K)}$.

4.3. Condensed hydrocarbon fraction
Figure 6 shows results of HC condensate content as a function of ambient air temperature at the different pressure ratios. At the pressure ratio of $\pi = 5$ and temperature difference of 28 K the mass flow of cold air was 22 kg/h. At the pressure ratio of $\pi = 7$ and temperature difference of 29.2 K the mass flow of cold air was 35 kg/h. At the ambient air temperature above 300 K system does not provide HC vapor condensation at all. The condensation efficiency increases with decreasing ambient temperature and reaches its maximum at the temperature of 273 K (42% of hydrocarbons are condensed by mass at $\pi = 7$ and 32.5% at $\pi = 5$). A further decrease in ambient temperature leads to a decrease in condensation efficiency. This is due to the fact that the initial mixture shown in Table 1 varies. Part of high-boiling hydrocarbons does not go into the vapor phase due to low temperatures and vapor with a large number of non-condensable components, such as air, methane, ethane, etc., enters the heat exchanger.
6. Conclusion

The paper studied the process of condensation of gasoline vapors using a countercurrent vortex tube in a complex in a shell-and-tube heat exchanger.

The results of an experimental study of countercurrent vortex tube are presented. Achieved parameters were of the studied vortex tube: maximum temperature difference for the cold flow 29.4 K at the cold flow fraction of $\mu = 0.55$ and pressure ratio of $\pi = 5$; the maximum temperature difference of the cold flow 32.7 K at the cold flow fraction of $\mu = 0.42$ and pressure ratio of $\pi = 7$ (figure 4). The maximum cooling capacity is 603.5 kJ/h at the cold flow fraction of $\mu = 0.65$ and $\pi = 5$; the maximum cooling capacity is 1068 kJ/h at the cold flow fraction of $\mu = 0.66$ and $\pi = 7$ (figure 5).

The heat exchanger was calculated in the UniSim Design R451 software package using the Steady State Rating model. The main geometrical parameters of the heat exchanger are calculated. The heat exchange area of this structure was 0.716 m$^2$. The heat transfer coefficient of the heat exchanger during the operation of the vortex tube at the pressure ratio of $\pi = 7$ and maximum cooling capacity was $UA = 193.5$ kJ/(h·K). The heat transfer coefficient of the heat exchanger during the operation of the vortex tube at the pressure ratio of $\pi = 5$ and maximum cooling capacity was $UA = 169.5$ kJ/(h·K).

It has been discovered that the efficiency of condensation of hydrocarbons by a countercurrent vortex tube is directly related to the ambient temperature and the cooling capacity provided by the vortex tube.

The proposed system produces maximum efficiency at an ambient temperature of 273 K (42% of hydrocarbons are condensed by mass at $\pi = 7$ and 32.5% at $\pi = 5$). At temperatures above 300 K, the system does not provide condensation of vapors at all. For these conditions, devices providing greater cooling capacity and temperature differential are required.

Further studies of the presented system in the laboratory are planned.

6. References

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