Development of a Scheme for Mixing Butane with Air for Gas Supply to Consumers

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Abstract. One of the promising development areas of gas supply systems is supplying butane-based air-and-gas mixtures to consumers. Butane-and-air mixture is fully adaptable to natural gas, taking into account the requirements for the interchangeability of combustible gases. However, we need to solve the problems of determining the mixture composition and developing a scheme for mixing butane with air taking into account the physical and chemical properties of butane that govern its operating at low inlet pressures providing a constant supply of source gas for mixing from an underground tank regardless of the climatic features in the region. Developing well-founded recommendations to obtain a mixture of butane with air will ensure the widespread introduction of such systems into the gas supply practice and enhance the uninterrupted operation of gas supply systems when using alternative combustible gases. On the basis of our research, we suggested a scheme for producing a mixture of butane with air using a dosing valve to ensure a constant supply of butane from an underground tank with alternating extraction of vapor and liquid gas phases and feeding the gas phase for mixing at the recommended pressure. We recommended a composition of butane-and-air mixture that meets the requirements of gas interchangeability and the maximum speed of flame propagation in gas burners during combustion.

Applying the scheme for producing a butane-and-air mixture of the recommended composition will allow to expand the possibility of gas supply to consumers when using alternative fuels, to relieve peak loads when supplying natural gas, and to ensure redundancy of gas supply systems for strategically important utility facilities.

1. Introduction

In line with the approved Development Framework for the Gas Industry in the Russian Federation until 2035, gasification of regions is carried out taking into account the availability and development of natural gas reserves in such regions, as well as using alternative energy sources, including liquefied and compressed natural gas (LNG and CNG), liquefied petroleum gas (LPG). By 2035, it is planned to increase the level of gasification to 83% on average. However, despite the high rates of gasification and the development of the gas pipeline system connected to the unified natural network gas supply system, gasification of remote regions, as provided for in the development strategy, will be implemented as mainly autonomous (using only liquefied/compressed natural gas (LNG, CNG) and liquefied petroleum gas (LPG)) or as a comprehensive gasification (by building both gas pipelines and autonomous gasification facilities) [2, 3].
Our analysis of scientific publications showed that the most suitable systems for this purpose are autonomous gas supply systems using gas-and-air mixtures based on liquefied petroleum gases, so called “propane-air” and “butane-air” systems [12, 16]. In turn, these systems can also serve as backup fuel, ensuring an uninterrupted gas supply to facilities in case of sudden drops in the gas pressure in the system, appearance of water condensation in pipelines, and “rolling” disconnections of consumers from the unified gas supply system. In this case, the gas supply is carried out with a mixture of propane or butane with air, and unlike systems running on a propane-butane mixture, these systems fully meet the condition of switching to natural network gas without reconfiguring the consumers’ gas-using equipment and re-laying the existing gas supply networks.

In the field of supplying gas-and-air mixtures to consumers, there are scientific papers by the following researchers: A.A. Ionin [4], A.P. Klimenko [5], A.K. Kortunov [6], E.V. Krylov [7], B.N. Kuritsyn [8, 9], N.N. Morozova [11], N.L. Staskevich [20], S.V. Zubkov [22], A.M. Tsirlin [21], as well as the studies of Research Institute for the Distribution and Use of Gas of Giproniigaz, OJSC [15], the Gazovik Center [1], World LPG Association (WLPGA) [19], Algas-SDI QM [10], Flüssiggas-Anlagen Salzgitter (FAS) [17], and Argonne National Laboratory [18] companies.

Developing autonomous gas supply systems in the Russian Federation using liquefied petroleum gases increases the share of butane consumption in public utilities. In the liquefied butane market, the volume of products manufactured in the Russian Federation in 2018 turned out to be around 6.8 million tons, with a 10.1% increase against 2017. The key district, where the highest production volume was recorded, is the Ural Federal District: its share was estimated at 65.5% or 4.5 million tons in kind. A wider use of butane in gas supply systems is supported by the fact that the cost of butane is 20% lower than the cost of propane. As shown by the current practice, autonomous gas supply systems with natural regasification are not designed in most cases for the use of liquefied gas with an increased content of butane fractions [7, 15, 20], whereas recommendations for the operation of systems running on technical butane are not at all mentioned in the known publications. Some aspects of the problem of increasing the vapor production of propane systems containing butane fractions are disclosed in papers by B.N. Kuritsyn and E.V. Krylov with regard to switching to fully artificial regasification or external heat supply for gas evaporation, without considering the possibility of natural butane evaporation [7, 9].

To developed recommendations for the use of gas supply systems with butane-based gas-and-air mixtures, we should solve the following main tasks:
- substantiation of the gas-and-air mixture composition that meets the conditions for the interchangeability of combustible gases;
- substantiation of the scheme for obtaining a gas-and-air mixture of the recommended composition.

To introduce recommendations for expanding the use of a butane-and-air mixture in the practice of gas supply to consumers, we need to conduct further research.

2. Theoretical formulation of the problem
The criterion determining the interchangeability of combustible gases is the Wobbe number. Interchangeability means the possibility of using an alternative gas without disrupting the normal operation of gas burners and without modifying their design solutions.

The Wobbe number for the butane-and-air mixture is calculated using the following formula [13]:

$$W_0 = d^{1/2} (Q_b^f)_{k_0} k_b^b$$  (1)

where \((Q_b^f)_{k_0}\) is the lower heat value of butane, MJ/cu.m [20]; \(k_b^b\) is the volume concentration of butane in the gas-and-air mixture, %; \(d\) is the relative density of the gas-and-air mixture by air, kg/cu.nm.

The relative density of the gas-and-air mixture by air is calculated using the following formula:

$$d = (\rho_b k_b^b + \rho_a k_a^b)\rho_a^{-1}.$$  (2)
where $k_a$ is the volume concentration of air in the gas-and-air mixture, %; $\rho_a$ is the specific density of air adopted as 1.29 kg/cu.nm; $\rho_b$ is the specific density of butane adopted as 2.7 kg/nm.cu.

To substantiate the composition of the butane-and-air mixture, we performed calculations using the following data:

- the lower heat value of butane: 118.53, MJ/cu.m;
- the change in butane content in the gas and air mixture: 1 to 100%.

The calculation results are shown in Fig. 1.

![Figure 1. To determine the optimal proportions of the butane-and-air mixture.](image)

As you can see from the graph in Fig. 1., the content of butane in the gas-and-air mixture must be at least 48% and not more than 54%. In this case, the gas-and-air mixture fully meets the requirements for the interchangeability of combustible gas. At the same time, for the trouble-free operation of gas-powered devices, interchangeable gases shall be different in terms of the maximum flame propagation speed by no more than 15–20%.

The normal maximum flame propagation speed for a gas-and-air mixture in a tube with a diameter of 25.4 mm, at a temperature of 20 °C, and a pressure of 101.3 kPa is calculated using the following formula:

$$W = (V_1 + V_2 + \ldots + V_n)^{-1} L \left( \frac{V_1 w_1}{l_1} + \frac{V_2 w_2}{l_2} + \ldots + \frac{V_n w_n}{l_n} \right)$$

(3)

where L is the content of compound gas in the combustible mixture, that ensures the maximum flame propagation speed, %; $V_1$, $V_2$,...,$V_n$ are the contents of simple gases in the combustible mixture, %; $w_1$, $w_2$,...$w_n$ are the maximum flame propagation speeds for simple gases in the combustible mixture,
m/s [4]; \( l_1, l_2, \ldots, l_n \) are the contents of simple gases in the mixture that ensure the maximum flame propagation speed, % [4].

The actual maximum flame propagation speed, taking into account the content of inert impurities (carbon dioxide and nitrogen) in the gas can be calculated using the following formula:

\[
W_{\text{act}} = W(1 - 0.01N_2 - 0.012CO_2)
\]

(4)

where \( W \) is the maximum flame propagation speed in the combustible mixture, m/s; \( N_2, CO_2 \) are the contents of nitrogen and carbon dioxide in the compound gas, %.

To determine the maximum normal flame propagation speed in the butane-based gas-and-air mixture, we performed relevant calculations. As the mixture of air with butane is calculated as an alternative to the natural gas, taking into account the perspective gasification with network natural gas, the maximum normal speeds were compared for natural gas and an air-gas mixture of the recommended composition.

For calculation, we have taken natural gas of the following composition: \( \text{CH}_4 - 87\%, \text{C}_2\text{H}_6 - 5.0\%, \text{C}_3\text{H}_8 - 1.6\%, \text{C}_4\text{H}_{10} - 0.7\%, \text{C}_5\text{H}_{12} - 1.8\%, \text{N}_2 - 3.0\%, \text{CO}_2 - 0.5\% \).

The composition of the recommended gas-and-air mixture: \( \text{C}_2\text{H}_6 - 2.0\%, \text{C}_3\text{H}_8 - 3.0\%, \text{C}_4\text{H}_{10} - 48\%, \text{air (O}_2 (21\%)+\text{N}_2 (79\%)) - 47\% \) [14].

According to the calculation results, the normal maximum flame propagation speed for natural gas is 0.7 m/s, and for butane-and-air mixture, 0.83 m/s. The divergence of the maximum speeds was 18.75%, which meets the recommended threshold for interchangeable combustible gases (15 to 20%) [4]. Therefore, the recommended gas-and-air mixture does meet the requirements for the combustible gas interchangeability, taking into account the recommended range of maximum flame propagation speeds.

3. **Practical part**

To produce butane-and-air mixture, we have suggested a scheme that allows for creating a mixture with the given parameters of mixed media at low inlet gas pressures. The mixing scheme and the dosing valve are shown in the figures (Fig. 2, Fig. 3):

![Figure 2. Scheme for supplying butane-and-air mixture to consumers: 1 – underground tank, 2 –](image)
liquid phase pipeline, 3 – filter, 4 – thermostat, 5 – float level controller, 6 – vaporizer, 7 – superheated vapor phase pipeline, 8 – superheated vapor phase reduction unit, 9, 20 – gas phase supply line, 10 – safety relief valve of the vaporizer, 11 – pump, 12 – check valve, 13, 21 – control pressure gauge, 14, 22 – safety relief valve, 15, 23 – safety shut-off valve, 16, 24 – pressure controller, 17 – vapor phase pipeline, 18 – gas filter, 19 – vapor phase reduction unit, 25 – multifunction valve for vapor phase extraction, 26 – valve for liquid phase extraction, 27 – three-way mixing valve, 28 – ready vapor phase pipeline, 29 – dosing mixing valve, 30 – air filter, 31 – compressor, 32 – air receiver, 33 – pretreated air pipeline, 34 – air heater, 35 – gas pipeline to the consumer.

**Operation Principle of the Scheme.** From underground tank 1, liquid butane is supplied via pipeline 2, thermostat valve 4, filter 3, and float level controller 5 into the annulus of vaporizer 6 equipped with safety relief valve 10. The resulting liquid gas vapors are superheated and supplied via pipeline 7 to reduction unit 8 and then, to pipeline 9. Upon a change in the gas flow within the capacity range of vaporizer 6, the liquid flow is regulated by float limit level controller 5. The pressure in pipeline 9 is controlled by pressure gauge 13. Upon excessive rise in this pressure, spring safety relief valve 14 bleeds part of the gas into the atmosphere. Upon excessive rise in the gas outlet pressure, safety shut-off valve 15 is activated that stops supplying gas to gas pipeline 9. The pressure in pipeline 9 is controlled by pressure controller 16.

**Specifics of the Butane Extraction from the Underground Tank.** From underground tank 1, liquid gas in the form of vapor phase is supplied, under the action of the pressure of its own vapors via pipeline 17 through filter 18 into reduction unit 19 that consists of pressure controller 24 and safety shut-off valve 23, and then, into pipeline 20. The pressure in pipeline 20 is controlled by pressure gauge 21. Upon excessive rise in this pressure, spring safety relief valve 22 bleeds part of the gas into the atmosphere. Upon excessive rise in the gas outlet pressure, safety shut-off valve 23 is activated that stops supplying gas to gas pipeline 20. The gas pressure in pipeline 20 is controlled by the pressure controller 24.

**Procedure for gas extraction from the underground tank.** The vapor phase is extracted via multifunction valve Multivalves (25), that operates in the presence of 698 kPa vapor phase pressure in the tank. When the pressure drops below 689 kPa, the valve is turned off and reactivated automatically when the vapor phase pressure in the tank rises above 698 kPa [1]. If valve 25 is turned off, liquid phase is supplied via valve 26.

**Equalizing the volume of the vapor phase produced.** Within the pressure range of 689 to 698 kPa, both valves 25 and 26 operate. In this case, the extraction control device is three-way valve 27 adjusted to the pressure of the vapor phase obtained during natural regasification. The three-way valve equalizes the vapor phase pressure and flow rate “downstream”, ensuring their constant value in gas pipeline 28. Upon decrease in the flow (pressure) of the vapor phase in gas pipeline 20, the valve admixes the required portion of gas from gas pipeline 9. Upon cutting off the gas supply via pipeline 20, the valve leaves only the gas flow from the gas pipeline 9 open.

**Mixing.** The mixture of butane with air is produced using dosing valve 29 that controls the air supply depending on the gas supply, maintaining a constant ratio of excess air in the mixture. The air supplied to valve 29 is pumped by compressor 31. The air taken from outdoors in the cold season is heated in air heater 34, passes the filtration stage 30, and is accumulated in receiver 32, that is required to equalize the pressure and volume of the air supplied.
Figure 3. Elementary diagram of the dosing valve: 1 – cylindrical body, 2 – diaphragm actuator, 3 – diaphragm capsule, 4 – diaphragm, 5 – sub-diaphragm cavity, 6 – gas inlet connector, 7 – spring, 8 – air inlet connector, 9 – gas pipeline, 10 – supra-diaphragm cavity, 11 – pulse holes, 12 – gas flow control valve, 13 – rod, 14 – pulse tube.

The dosing valve is a device with cylindrical body 1 wherein diaphragm capsule 3 is installed. Diaphragm capsule 3 is divided by diaphragm 4 into two cavities 5 and 10. Its lower side is exposed to excess gas pressure supplied via connector 6 from the pipeline. The pressure on diaphragm 4 is equalized by working spring 7. Movement of the diaphragm changes the cross-sectional area of air connection 8 by valve 12 through which air is supplied to the pipeline 9.

The diaphragm in cavity 10 is also exposed to excess gas pressure supplied via pulse tube 14 having pulse holes 11. Pulse tube 14 is installed in the body of rod 13 actuating valve 12.

4. Conclusion
1. We have recommended the composition of butane-and-air mixture with the butane content in the gas-and-air mixture to be not less than 48% and not more than 54%. We have checked the maximum flame propagation speed in gas burners for the recommended mixture composition. The maximum speed divergence was 18.75%, which corresponds to the recommended threshold for interchangeable combustible gases.

2. The use of the suggested scheme for producing butane-and-air mixture of the recommended composition will allow to expand the possibility of gas supply to consumers using alternative fuels, to relieve peak loads when supplying natural gas, and to ensure redundancy of gas supply systems for strategically important utility facilities.

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