Calculation of Energy Parameters of LNG Power Plant with Utilization its Cold Energy

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Abstract. This paper proposes the possibility of using a cryogenic power plant as part of a hybrid engine, which can be used in the system of urban transport infrastructure. The model of this cryogenic power plant consists of main contour and auxiliary contour of power plants. The parameters of a hybrid cryogenic power plant were evaluated and the characteristics of the main contour of a hybrid power plant driven by a piston expander and a turbo expander with heat input from both the ambient and the exhaust gases of a diesel engine were calculated. Liquid methane is used as the main fuel. The optimal operation cycle of the auxiliary contour of power plant itself has been determined. For this purpose the main parameters of Rankin and Brayton cycles have been analyzed - consumption, power, efficiency. Besides, the most suitable cryogenic fuels for efficient operation were determined and the schemes of the plants were proposed. The calculations were performed using calculation algorithms, examples of which are presented in this article.

1. Introduction

Reducing the growth of urban air pollution and greenhouse gas emissions from vehicle exhaust pipes is the main motivation for the development of alternative transport technologies that are not dependent on burning fossil fuels. Technological solutions such as the creation of a hybrid engine will eliminate the emission of automobile combustion products in areas with low air quality, as well as reduce the net amount of pollutants emitted into the environment. A thorough review of the overall environmental impact, efficiency and capacity is necessary to assess the ability of any new transport system to meet the needs of society [1].

This paper proposes a possible solution to the problem for urban transport infrastructure. It is proposed to use a hybrid cryogenic power plant, which consists of two contours: the main and auxiliary. The fuel in the main contour is methane, in the auxiliary contour - cryogenic fuel, the most effective for the system. It is proposed to implement four possible schemes of a power plant:

1. Cryogenic power plant driven by a piston expander;
2. Cryogenic power plant driven by a piston expander with the supply of heat of exhaust gases;
3. Cryogenic power plant driven by a turboexpander;
4. Cryogenic power plant driven by a turboexpander with the supply of heat of exhaust gases.
Nomenclature

| Symbol | Description |
|--------|-------------|
| G<sub>СН4</sub> | Methane consumption (kg/sec) |
| p | Pressure (Pa) |
| T | Temperature (K) |
| d | Cylinder diameter (m) |
| φ | Crank angle (°) |
| V<sub>cyl</sub>(φ) | Cylinder working area volume (m<sup>3</sup>) |
| V<sub>c</sub> | A measure of the minimum gap between piston and cylinder head (m<sup>3</sup>) |
| V<sub>h</sub> | Volume inside the expansion chamber that is not occluded by the piston (m<sup>3</sup>) |
| n | RPM |
| l(φ) | Length of stroke |
| R | Ratio of connecting rod to crank radius |
| Q(φ) | Heat transfer (kJ) |
| K<sub>s</sub> | Heat transfer coefficient (W/m<sup>2</sup>K) |
| δ<sub>w</sub> | Wall thickness (m) |
| λ<sub>w</sub> | Coefficient of thermal conductivity (W/mK) |
| α<sub>s</sub> | Heat dissipation coefficient (W/m<sup>2</sup>K) |
| N<sub>т</sub>| Nusselt number |
| W<sub>m</sub>, W<sub>a</sub>| Power of the main and auxiliary circuit |
| H<sub>т0</sub> | Heat transfer turbine expander (kJ/kg) |
| H<sub>0т</sub> | Available heat loss (kJ/kg) |
| ρ<sub>z</sub> | Gas density behind the last stage (kg/m<sup>3</sup>) |
| ΔP | Pressure drop (Pa) |
| π<sub>т</sub> | Expansion ratio of the turbo expander |
| F<sub>w</sub>(φ) | Total cylinder surface area (m<sup>2</sup>) |
| F<sub>p</sub> | Piston area (m<sup>2</sup>) |
| F<sub>h</sub> | Inner area of the cylinder head (m<sup>2</sup>) |
| t<sub>r</sub> | Piston ring thickness (m) |
| F<sub>c</sub> | Clearance surface area (m<sup>2</sup>) |
| γ | Adiabatic exponent |
| m | Mass flow rate of the working fluid (kg/sec) |
| h | Enthalpy (kJ/kg) |
| Q<sub>1</sub> | Heat input (kJ) |
| N | Power (kW) |
| N<sub>т</sub> | Specific power (kW) |
| η | Thermodynamic efficiency |
| η<sub>т</sub> | Turboexpander efficiency |
| C<sub>p</sub> | Isobaric heat capacity (J/kg) |
| π<sub>т</sub> | Expansion ratio of the turbo expander |
| η<sub>м</sub> | Mechanical efficiency |
| N<sub>т</sub>| Turboexpander power (kW) |
| W<sub>т0</sub>| Liquefied gas single stage heat difference |
| H<sub>т0</sub>| Single stage heat difference (kJ/kg) |
| H<sub>т</sub>| Kilogram of the substance used in a turboexpander (kJ/kg) |
| H<sub>0т</sub>| Calculation of the expansion effect of one turboexpander (kJ/kg) |
| z | Number of stages of turboexpander |
| α<sub>т</sub> | Heat recovery coefficient |
| c | Velocity (m/sec) |

2. Initial data

In the developed hybrid power plant it is proposed to use methane at cryogenic temperatures. An open contour of a power plant using low-potential heat of a cryoproduct is the most simple and economical [2]. Figure 1 illustrates the T-s diagram of the Rankine cycle. The Rankine cycle consists of several sequential processes: adiabatic compression in a pump 1-2, heating to a boil 2-3, boiling process 3-4, superheat 4-5, adiabatic expansion 5-5’, additional superheat 5-7 [3].
The advantage of the presented scheme for the implementation of the Rankine cycle is the low consumption of the working fluid and the possibility operating of the cycle at high degrees of pressure increase $n_k$.

In this power plant, the parameters of the coolant at point 1: $p_1 = 0.5 \text{ MPa}; T_1 = 139 \text{ K}$.

Since the ambient temperature varies on average from 240 to 280 K depending on the time of the year and day cycles are considered taking into account three variants of temperature values at point 5, with $\Delta T = 10 \degree$.

3 variants of the Rankine cycle:
- $p_{2,3,4,5} = 3288 \text{ kPa} - \text{pressure at points 2, 3, 4, 5}; T_{3,4} = 180 \text{ K} - \text{temperature in points 3, 4}$.
- $p_{2,3,4,5} = 3854 \text{ kPa} - \text{pressure at points 2, 3, 4, 5}; T_{3,4} = 185 \text{ K} - \text{temperature in points 3, 4}$.
- $p_{2,3,4,5} = 4641 \text{ kPa} - \text{pressure at points 2, 3, 4, 5}; T_{3,4} = 190,55 \text{ K} - \text{temperature in points 3, 4}$.

Based on the calculations of the four options for the Rankine cycle, the most suitable option is selected that matches the declared capacity $N=265 \text{ kW}, G_{\text{CH}_4}=0.017 \text{ kg/sec}$.

3. Calculation of the parameters of the main contour of cryogenic power plant driven by a piston expander

The layout of cryogenic power plant driven by a piston expander with heat input from the ambient is shown in Figure 2 (A), and cryogenic power plant driven by a piston expander with the heat supply of exhaust gases shown in Figure 2 (B).

Cryogenic fluid (liquid methane) from tank 1 with the help of pump 2 enters heat exchanger 3. Next gaseous enters piston expander 5 (Figure 2), where a polytropic expansion process occurs through heat inflows through the walls of the cylinder and piston ($1 \leq n \leq k$) [4].

The auxiliary contour of a power plant also includes: a heat exchanger-evaporator 11, pump 10, turbine 12 and a cryogenic working fluid heat exchanger 3. The energy obtained in the combustion process is transmitted to the electric generator 13 and is accumulated in the battery 16. The energy from the auxiliary contour turbine 12 and expander 5 of the main contour is transmitted to the generator 13 and 14 and goes to the drive.

The piston expander is a cylinder with a diameter $d = 260 \text{ mm}$, outlet gas pressure is 0.5 MPa and a temperature is 290 K.

Initial data: $G_{\text{CH}_4}=0.017 \text{ kg/sec, } p_{\text{input}} = 0.5 \text{ MPa, } T_{\text{input}} = 290 \text{ K}$.

The piston expander is a cylinder with a diameter is $d = 260 \text{ mm}$, outlet gas pressure is 0.5 MPa and a temperature is 290 K.
The calculations were carried out and the geometric characteristics of the expander were determined in accordance with the methods [5].

The calculation algorithm is presented in Figure 3.

**Figure 3.** The calculation algorithm of a cryogenic power plant driven by a piston expander

4. Calculation of the parameters of the main contour of cryogenic power plant driven by a turboexpander

**Figure 4.** Diagram of a cryogenic power plant driven by a turboexpander

a) with heat supply from the environment  b) with the supply of heat of exhaust gases

1 - tank with liquid methane, 2 - pump, 3 - evaporator heat exchanger, 4 - additional heat exchanger, 5 - turboexpander, 6 - heat exchanger-heater, 7 - internal combustion engine, 8 - gearbox, 9 - mover, 10 - pump, 11 - heat exchanger, 12 - turbine, 13,14 - generator, 15 - controller, 16 - battery, 17 - electric motor
The layout of cryogenic power plant driven by a turboexpander with heat input from the ambient is shown in Figure 4 (A), and cryogenic power plant driven by a turboexpander with the heat supply of exhaust gases shown in Figure 4 (B). The principle of operation of a power plant driven by a turboexpander is similar to the principle of a power plant driven by a piston expander. The calculation algorithm is presented in Figure 5.

5. The choice of optimal parameters of the power plant of the auxiliary contour
It is proposed to use a heat engine operating according to the Rankine cycle [6] or Brayton cycle [7] as the power plant for the auxiliary circuit. The auxiliary contour of the power plant (Figure 6) can operate on various cryogenic fuels: methane, ethane, krypton, xenon.

An estimate of the amount of additional electrical energy received is given in tables 1 and 2.
**Table 1. Estimation of the amount of received additional electric energy**

|               | Rankine cycle | Brayton cycle | πk = 2 | πk = 2.5 | πk = 5 | πk = 10 |
|---------------|---------------|---------------|--------|----------|--------|---------|
| q1, kJ/kg     | q2, kJ/kg     | L, kJ/kg      | G, kg/s| N, kW    | ηt, %  |         |
| Methane (p=0.6 MPa) | 795  | -595  | 395   | 0.015   | 11.58  | 25      |
| Ethane        | 598  | -500  | 500   | 0.017   | 10.37  | 16      |
| Krypton       | 122  | -97   | 97    | 0.089   | 10.90  | 20      |
| Xenon         | 92   | -83   | 83    | 0.104   | 9.61   | 10      |
| Methane (p=0.7 MPa) | 770  | -600  | 400   | 0.014   | 11.13  | 22      |
| Methane (p=0.6 MPa) | 260  | 220   | 40    | 0.039   | 1.6    | 15      |
| Ethane        | 118  | 110   | 8     | 0.079   | 0.6    | 7       |
| Krypton       | 23.5 | 18    | 5.5   | 0.482   | 2.6    | 23      |
| Xenon         | 3    | 2.5   | 0.5   | 3.468   | 1.7    | 17      |
| Methane (p=0.7 MPa) | 255  | 202   | 53    | 0.043   | 2.3    | 21      |
| Methane (p=0.6 MPa) | 222  | 175   | 47    | 0.050   | 2.3    | 21      |
| Ethane        | 92   | 80    | 12    | 0.108   | 1.3    | 13      |
| Krypton       | 13   | 10    | 3     | 0.867   | 2.6    | 23      |
| Xenon         | 2.5  | 2     | 0.5   | 4.335   | 2.2    | 20      |
| Methane (p=0.7 MPa) | 215  | 147   | 68    | 0.059   | 4.0    | 32      |
| Methane (p=0.6 MPa) | 170  | 102   | 68    | 0.085   | 5.8    | 40      |
| Ethane        | 81   | 65    | 16    | 0.133   | 2.1    | 20      |
| Krypton       | 3    | 2.5   | 0.5   | 3.468   | 1.7    | 17      |
| Xenon         | -    | -     | -     | -       | -      | -       |
| Methane (p=0.7 MPa) | 165  | 107   | 58    | 0.081   | 4.7    | 35      |
| Methane (p=0.6 MPa) | 85   | 40    | 45    | 0.217   | 9.8    | 53      |
| Ethane        | 50   | 30    | 20    | 0.289   | 5.8    | 40      |
| Krypton       | -    | -     | -     | -       | -      | -       |
| Xenon         | -    | -     | -     | -       | -      | -       |
| Methane (p=0.7 MPa) | 95   | 47    | 48    | 0.184   | 8.9    | 51      |

**Conclusion:** Based on the data obtained, it can be concluded that it is most efficient to use an auxiliary contour of the power plant with heat supply from the environment operating according to the
Rankine cycle, using liquid methane as a working substance at a pressure is 0.6 MPa. Power \( N = 11.6 \) kW, efficiency is 20% at a flow rate is \( G = 0.015 \) kg/s.

**Table 2.** Estimation of the amount of additional electric energy received by the cryogenic power plant with the supply of heat of exhaust gases.

|                   | Rankine cycle | Brayton cycle |                        |                        |
|-------------------|---------------|---------------|------------------------|------------------------|
|                   | \( q_1, \) kJ/kg | \( q_2, \) kJ/kg | \( L, \) kJ/kg | \( G, \) kg/s | \( N, \) kW | \( \eta, \) % |
| Methane (p=0.6 MPa) | 1398.64       | -445.14       | 445.14             | 0.019               | 27.2       | 68%         |
| Ethane            | 1160.09       | -434.76       | 4344.76            | 0.020               | 23.1       | 63%         |
| Krypton           | 196.50        | -97.18        | 97.18              | 0.089               | 17.5       | 51%         |
| Xenon             | 136.29        | -86.60        | 86.6               | 0.100               | 13.6       | 36%         |
| Methane (p=0.7 MPa) | 1616.42       | -438.95       | 438.95             | 0.020               | 31.9       | 73%         |

|                   | \( \pi_k = 2 \) |                        |                        |                        |
| Methane (p=0.6 MPa) | 1040.6         | 787.7          | 252.9              | 0.011               | 2.75       | 24%         |
| Ethane            | 795.0          | 559.0          | 236.1              | 0.015               | 3.62       | 30%         |
| Krypton           | 103.2          | 84.4           | 18.8               | 0.102               | 1.91       | 18%         |
| Xenon             | 56.0           | 46.4           | 9.5                | 0.185               | 1.76       | 17%         |
| Methane (p=0.7 MPa) | 1031.9         | 789.7          | 242.2              | 0.011               | 2.63       | 23%         |

|                   | \( \pi_k = 5 \) |                        |                        |                        |
| Methane (p=0.6 MPa) | 949.5          | 505.4          | 444.1              | 0.017               | 7.53       | 47%         |
| Ethane            | 703.2          | 314.8          | 388.5              | 0.027               | 10.57      | 55%         |
| Krypton           | 90.7           | 57.3           | 33.3               | 0.149               | 4.98       | 37%         |
| Xenon             | 44.7           | 28.1           | 16.6               | 0.305               | 5.06       | 37%         |
| Methane (p=0.7 MPa) | 940.7          | 498.5          | 442.2              | 0.017               | 7.60       | 47%         |

|                   | \( \pi_k = 10 \) |                        |                        |                        |
| Methane (p=0.6 MPa) | 861.2          | 353.1          | 508.1              | 0.024               | 12.33      | 59%         |
| Ethane            | 604.1          | 192.3          | 411.9              | 0.045               | 18.35      | 68%         |
| Krypton           | 81.9           | 40.9           | 41.0               | 0.209               | 8.58       | 50%         |
| Xenon             | 35.5           | 17.5           | 18.0               | 0.489               | 8.80       | 51%         |
| Methane (p=0.7 MPa) | 847.1          | 345.6          | 501.4              | 0.025               | 12.43      | 59%         |
Conclusion: Based on the data obtained, it can be concluded that it is most efficient to use an auxiliary contour of the power plant with heat supply from exhaust gases operating according to the Rankine cycle, using liquid methane as a working fluid at a pressure is 0.7 MPa. Power \( N = 31.9 \) kW, efficiency is 73% at flow rate is \( G = 0.020 \) kg/s.

6. Comparison of the energy efficiency of hybrid power plants
Table 3 presents the main comparative parameters of cryogenic plants driven by a piston expander and a turboexpander.

**Table 3.** Comparison of energy parameters of cryogenic power plants

| Cryogenic power plant driven by a piston expander | \( N_{en}, \) kW | \( N_{mc}, \) kW | \( N_{ac}, \) kW | \( N_{\Sigma}, \) kW | \( \eta \) | \( \eta_{\Sigma} \) |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|--------|--------|
| Cryogenic power plant driven by a turboexpander | 265             | 1.1             | 11.6            | 277.7           | 0.39   | 34.5%  |
| Cryogenic power plant driven by a piston expander with the supply of heat of exhaust gases | 265             | 3.75            | 11.6            | 280.35          | 0.67   | 35%    |
| Cryogenic power plant driven by a turboexpander with the supply of heat of exhaust gases | 265             | 1.1             | 31.9            | 298             | 0.39   | 37.1%  |
| Cryogenic power plant driven by a turboexpander with the supply of heat of exhaust gases. | 265             | 3.75            | 31.9            | 300.65          | 0.67   | 37.4%  |

Where \( N_{mc}, N_{ac} \) и \( N_{\Sigma} \) – installation power of the main and auxiliary circuits and total power, respectively.

\[
\eta_{\Sigma} = \frac{Q_1 \eta_1}{Q_2} \cdot \eta_m \cdot \eta_g \cdot \eta_b
\]

We can be seen from the point of view of calculating the efficiency of the energy parameters of power plants, the most efficient is a power plant driven by a turboexpander with an efficiency of 67%, however, the turboexpander has structural difficulties, vibrations and large weight and size characteristics. The efficiency of the power plant driven by a piston expander is 39%, the advantage of a piston expander is its relatively low cost and proven technology for its manufacture.

7. Conclusion
Based on the studies, the following conclusions:

A. It is proposed to use a hybrid power plant for driving a bus, consisting of a power plant of the main contour driven by a turboexpander and a power plant of the auxiliary contour, which will solve the environmental problems of large cities without compromising market competitiveness in terms of efficiency.

B. The calculation results show that it is most efficient to use power plant with a supply of heat of exhaust gases operating according to the Rankine cycle using liquid methane as a working fluid at a pressure is 0.7 MPa, \( G_{CH_4} = 0.020 \) kg/s, \( N_{acpp} = 31.9 \) kW and \( \eta = 78\% \). As well as plants with a supply of ambient heat operating on the Rankine cycle using liquid methane as a working fluid at a pressure is 0.6 MPa, \( G_{C_2H_6} = 0.015 \) kg/s, \( N_{acpp} = 11.6 \) kW and \( \eta = 20\% \).

C. Analysis of the calculations shows that it is most efficient to use power plants of the auxiliary contour operating according to the Rankine cycle with the supply of heat of exhaust gases using liquid methane or liquid ethane as a working fluid. From the point of view of economy, methane is the most suitable working fluid for the auxiliary contour of power plant.

D. A comparative analysis of power plants showed that the most optimal power plant is a power plant driven by a turboexpander \( N = 265 \) kW, \( \eta = 61\% \). The total power of the power plant is \( N = 300.65 \) kW.
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