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ANALYSIS OF THE WORKING PROCESS IN A RECIPROCATING EXPANDER IN THE REGION OF WET VAPOR

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By means of a numerical experiment with the example of methane, we analyze the features of the working process of a reciprocating expander with heat release associated with condensation, friction, and external heat exchange. The influence of the technical characteristics of expanders and inlet gas parameters is also considered.

Introduction. In modern reciprocating expanders, the expansion process can be realized not only in the region of superheated vapor when the working gas at the inlet and outlet does not change the state, but also in the region of wet vapor when in the process of expansion partial condensation occurs. Such reciprocating expanders used in cryogenic plants are called "gas-liquid" of "two-phase" expanders. Carrying adiabatic expansion over into the region of wet vapor can create prospects for decreasing energy costs to liquefy gases [1].

Character of the Change in Methane Parameters in a Reciprocating Expander in Pressure Condensation. The mathematical model describing the processes of cooling and partial condensation of the gas as it expands in a reciprocating expander developed by us [2] takes into account the formation of liquid phase nuclei according to Ya. I. Frenkel's theory and the growth of drops, as well as the real thermophysical properties of the gas. In the adiabat equation, the internal heat release due to the phase transition is taken into account.

The character of the change in the gas parameters in the presence of condensation (without friction and external heat inflows) has been considered for a methane small-size expander [3], whose technical characteristics are given below in the corresponding section with a comparative analysis of the operation of expanders of various standard sizes. Five variants of the initial (inlet) parameters: p_0 = 4 MPa, T_0 = 198, 203, 209, 215, and 223 K have been considered. A *p–H* diagram of methane (Fig. 1) based on the advanced equation of state [4] and complemented by isotherms corresponding to supersaturated vapor has been calculated. The *p–H* diagram illustrates the character of the change in the methane parameters in a reciprocating expander in the presence of condensation.

The gas parameters in the expander first change according to the isentropic expansion law (without condensation). On going to the region of wet vapor and reaching critical supersaturation, nucleation, condensation growth of methane drops, and the corresponding heat release begin. As a result, the process departs from the adiabat. If the volume heat release having the same dimensions as the pressure exceeds in value the current pressure, then the gas temperature will begin to increase. In so doing, the supersaturation decreases. As a result, S_{sup} becomes close to unity, the state parameters of methane approach values corresponding to the condensation line, and the nucleation ends. Such a process is given in Fig. 1 in the region of wet vapor by curves 1–3. Under the initial conditions corresponding to curves 4 and 5, condensation has no time to develop, liquefaction practically does not occur, and the gas parameters in the process of expansion correspond to the adiabats.

Under the conditions being considered at the inlet to the expander, the values of the outlet parameters (at the end of a stroke of the piston towards gas expansion) for all variants of initial conditions are close, and the difference is in the liquefaction coefficients. Therefore, the choice of the inlet gas parameters for the expander is determined by the problem solved in each particular case and by the technical abilities of the expander.

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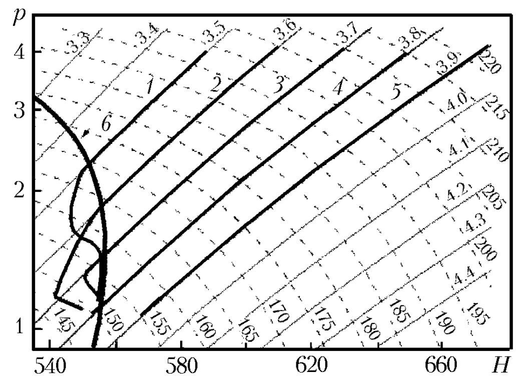

Fig. 1. p–H diagram of methane: 3.3, 3.4, 3.5, 3.6, ..., 4.4, entropy values, kJ/(kg·K); 145, 150, 155, 160, ..., 220, temperature values, K; 1, 2, 3, 4, and 5, processes of cooling and partial liquefaction of methane in the expander corresponding to p_0 = 4 MPa and, respectively, to T_0 = 198, 203, 209, 215, and 223 K (in methane expansion only the condensation heat release is taken into account); 6, boundary curve. p, MPa; H, kJ/kg.

Influence of Friction and External Heat Exchange on the Working Processes in the Expander. The heat inflows caused by the mechanical friction and the heat exchange with the environment strongly influence the efficiency of the expander. They, as does the condensation heat release, lead to the appearance of heat sources in the expansion machine. Consider the process in which the gas in the reciprocating expander is only cooled (without condensation). The heat generated as a result of the friction of the piston rings as well as the external heat inflow heat the cylinder wall. Then the heat from the wall is transferred to the gas and, as a result, the state parameters of the gas deviate from the adiabat. In the calculations, this summed heat inflow to the gas is assumed to be averaged over the period of the working stroke of the piston.

The equation that permits calculating the gas parameters upon expansion in the reciprocating expander with account for both the condensation heat release and the friction and external heat inflows has the form [2]

$$T_2 = T_1 \left[\frac{p_2 - A_{\text{eff}} B}{p_1 - A_{\text{eff}} B} \right]^{(A_{\text{eff}} - 1)} \frac{p_2}{p_1},$$

where $A_{\text{eff}} = (k_{\text{eff}} - 1)/k_{\text{eff}}$. This equation holds for a small step of change in the state parameters in the zonal calculation. For the methane expander [3], such calculations have been performed for isentropic expansion, expansion with account for the condensation alone, expansion with account for the friction and external heat inflows (without condensation), as well as for expansion under the simultaneous influence of all the above factors at the inlet parameters T_0 = 198 K, p_0 = 4 MPa, S_0 = 3.5 kJ/(kg·K) and T_0 = 203 K, p_0 = 4 MPa, S_0 = 3.6 kJ/(kg·K) corresponding to the beginning of condensation.

The isentropic calculation gives the lowest values of T and p at the end of expansion. In the zonal calculation of the expansion with account for the friction and external heat inflows, the value of the volume heat release corresponding to the averaged heat inflow remained unaltered as opposed to the volume condensation heat release. In the calculation, the B values were varied so that the pressure at the end of expansion slightly exceeded the pressure at the end of the isentropic process. In was assumed that this excess was 3 to 6% as η_{ad} was changed from 0.81 to 0.62, and at other close values of the pressure at the outlet the final results of the calculation change slightly. For the output values of the adiabat calculated by the given η_{ad}, the corresponding T and S exceeding the isentropic values were determined. As η_{ad} decreases from 0.81 to 0.62, the value of B increases. At the initial parameters assumed, this volume heat release corresponding to the influence of the friction and the external heat inflow was varied from 0.14 to 0.35 MJ/m^3.

At the next stage of calculation, the simultaneous influence of the condensation, the friction, and the external inflows were taken into account. In this case, the previously calculated volume heat release at each step of zonal cal-

TABLE 1. Methane Parameters at the End of Expansion in the Methane Stage of the Expander [3] under the Inlet Conditions: S_0 = 3.5 kJ/(kg·K), T_0 = 198 K, p_0 = 4 MPa, H_0 = 588 kJ/kg

Expansion	η_{ad}	T, K	p, MPa	S, kJ/(kg·K)	H, kJ/kg	K_{liq}, %
Isentropic	1	138	1.11	3.50	510	—
Nonisentropic with account for:						
condensation	1	154	1.24	3.76	557	4.0
friction and external heat inflows	0.81	142	1.15	3.57	520	
	0.78	143	1.15	3.59	524	—
	0.72	145	1.17	3.61	529	—
	0.67	146	1.18	3.64	534	—
	0.62	148	1.19	3.67	539	—
condensation, friction, and external heat inflows	0.81	154	1.24	3.76	556	3.0
	0.78	154	1.24	3.76	556	2.7
	0.72	154	1.24	3.76	556	2.3
	0.67	154	1.24	3.75	556	1.8
	0.62	152	1.23	3.74	551	1.1

Note. The value of η_{ad} corresponds to the change in the parameters connected with the friction and heat exchange without account for the condensation.

culation was increased by a value corresponding to the variable condensation heat release due to the nucleation and the growth of drops by the method of [2]. Hereinafter only the expansion process is considered and the pressure loss in expander charge and gas discharge are not taken into account since their fraction is relatively small.

The results of calculations for the initial conditions corresponding to S_0 = 3.5 kJ/(kg·K), T_0 = 198 K, p_0 = 4 MPa are presented in Table 1. The values of the methane parameters at the end of expansion at different values of η_{ad} for the calculation variants taking into account either the condensation alone or the simultaneous influence of the condensation, friction, and heat inflows practically agree, but when the above factors are simultaneously taken into account, the liquefaction coefficient markedly decreases. The exception is the variant of calculation for which η_{ad} = 0.62, i.e., when the influence of the friction and external heat inflows is strong.

Under the initial conditions corresponding to S_0 = 3.6 kJ/(kg·K), T_0 = 203 K, p_0 = 4 MPa the influence of the friction and external heat inflows is significant, and at η_{ad} = 0.81 and 0.78 the liquefaction coefficient is 0.6 and 0.04%, respectively, whereas in the absence of the influence of the above factors K_{liq} = 2.7%. At η_{ad} = 0.72 the condensation process in the cylinder has no time to begin at all.

Figure 2 shows the change with time in the medium parameters in the expander cylinder in the process of methane expansion for the calculation variants in which only the condensation heat release (curves 1) and the simultaneous influence of the condensation, friction, and external heat inflows (Figs. 2 and 3, η_{ad} = 0.81 and 0.67) are taken into account. At the beginning of the piston motion towards expansion the temperature curves 2 and 3 lie higher compared to curve 1 (Fig. 2a). An increase in the temperature leads to the fact that condensation begins later. The peaks corresponding to an increase in the number of nuclei and complete heat release in a unit volume shift to a later time of the piston stroke and become smaller (Fig. 2b and c). As a result, in the presence of condensation, friction, and external heat inflows by the end of expansion the number of drops in a unit volume is smaller (Fig. 2d), and the liquefaction coefficient decreases. However, the drops that have grown by the end of expansion in the presence of friction and external heat exchange are larger. Such a property of the condensation process is explained as follows. At each step of zonal calculation the equation for the diameter of the growing drop was used. At low values of the Knudsen number it is of the form [2]

$$\delta_2^2 - \delta_1^2 = 4Q\Delta\tau/\rho_{liq},$$

where $Q = 2\lambda_v(T_d - T_\infty)/r$ at Nu = 2. This equation includes both the difference between the temperatures of the drop and the medium and the thermophysical properties of methane that change with temperature. The estimates have shown that the joint influence of these factors leads to an increase in the diameter of these drops.

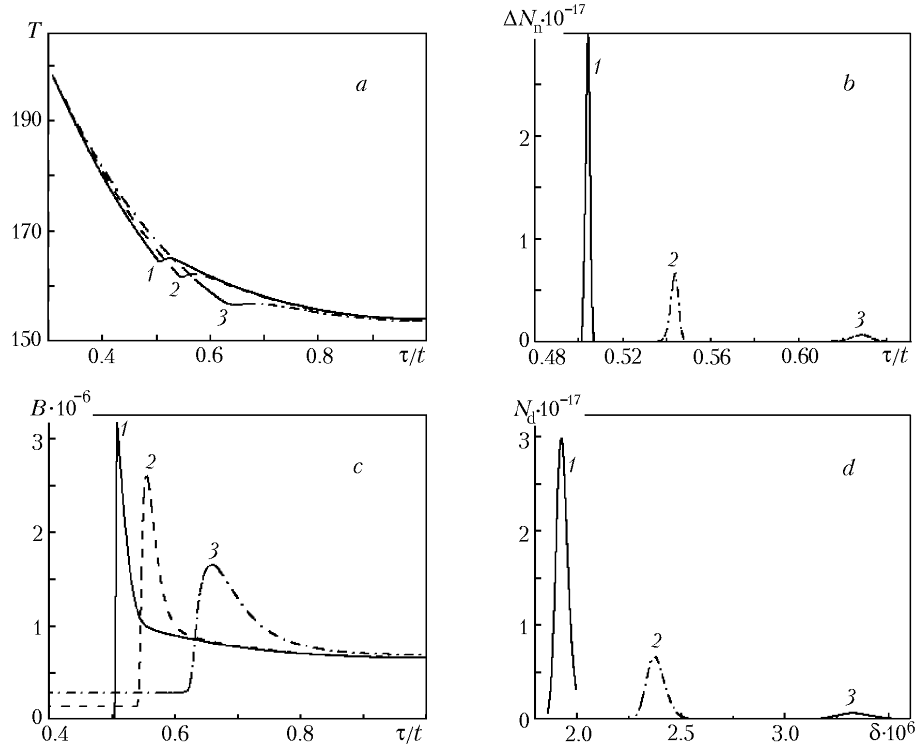

Fig. 2. Time dependences of the temperature T of methane in the expander [3] (a); increments of the number of nuclei in a unit volume ΔN_n (b); of the volume heat release B (c); dependence of the number of drops grown in a unit volume N_d on the diameter δ by the instant of time τ/t = 0.9 (d). Inlet conditions: S_0 = 3.5 kJ/(kg·K), T_0 = 198 K, p_0 = 4 MPa: in methane expansion only the condensation heat release (1), as well as the simultaneous influence of the condensation and friction with external inflows are taken into account at η_{ad} = 0.81 (2) and 0.67 (3). T, K; ΔN_n, N_d, 1/m^3; B, J/m^3.

In [3], an attempt was made to directly take into account the influence of the heat sources connected with the external heat exchange and friction on the gas parameters in reciprocating expanders. According to the results of the calculation [3], taking into account the real thermophysical properties of methane, for the input parameters, when the condensation in the expander is absent, the influence of friction and external heat inflows decreases the value of the adiabatic efficiency insignificantly. For instance, for the methane expander at T_0 = 300 K and p_0 = 4 MPa, η_{ad} changes from 0.896 (heat exchange is absent, and the difference of η_{ad} from unity is due to the pressure loss at the inlet of methane to the expander and at the outlet from it) to 0.856 with account for the friction and heat inflows. If such a value of η_{ad} remains unchanged at the initial parameters when condensation in the expander is possible, then the liquefaction coefficient can be fairly high.

Influence of the Technical Characteristics of Reciprocating Expanders on the Working Process. With increasing size of the expander cylinder the intensity of the heat exchange between the gas and the chamber walls, all other things being equal, decreases which should improve the efficiency of the machine [5]. Let us consider the processes in reciprocating expanders of six standard sizes [3, 5, 6] (Table 2). In this section, as in the previous ones, in the numerical experiment for the chosen expanders, the value of the relative dead space of the cylinder a, as well as the value of the relative stroke of the piston at the instant of termination of filling the cylinder with the gas C, were taken to be equal to 0.25 (in the cases where other values of C were used, this is specified specially). Zonal calculations of methane parameters have been made at an inlet pressure p_0 = 4 MPa and at initial temperatures T_0 equal to 198 and 203 K corresponding to entropy values of 3.5 and 3.6 kJ/(kg·K). The calculations have been made for both the case where only the condensation heat release is taken into account and for the variant in which the simultaneous influence of the condensation, friction, and external heat inflows at η_{ad} values from 0.81 to 0.62 are considered. The

TABLE 2. Technical Characteristics on Reciprocating Expanders

Expander characteristics	Methane stage [3]	Air stage [3]	DSD-5 [6]	ZaD-11/50 [6]	DKA 750-20/1 [5]	MDKA 500-70/5 [5]
Cylinder diameter, m	0.042	0.110	0.08	0.13	0.125	0.08
Piston stroke, m	0.066	0.066	0.18	0.19	0.11	0.11
Rotation frequency, rpm	980	980	180	187/370	1500	1000

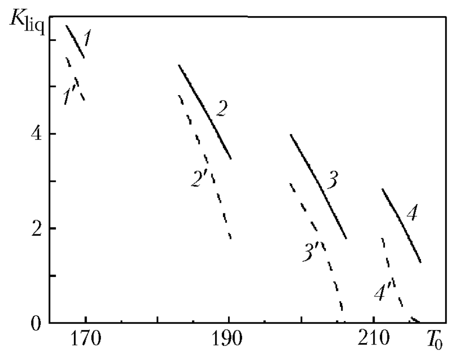

Fig. 3. Dependence of the liquefaction coefficient of methane K_{liq} in the reciprocating cylinder [3] on the initial temperature T_0 and the initial pressure: 1–4) p_0, respectively, of 2, 3, 4, and 5 MPa in the absence of friction and external heat inflows; 1′–4′) the same initial pressures but η_{ad} = 0.81; K_{liq}, %; T_0, K.

calculations for all chosen expanders have shown that the parameters of methane corresponding to the end of the expansion process practically coincide. However, in the case where condensation occurs in the cylinder, the technical characteristics of the expanders can influence the change in individual parameters of the vapor-liquid mixture, in particular, the number and size of drops formed. If such an expanding machine as a reciprocating expander is used with the aim of gas condensation, then information about these parameters is important.

Calculations have shown that the rotation frequency of the shaft n has no appreciable influence on the change in the methane parameters during a piston stroke towards expansion. Estimates have been made for stages of ZaD-11/50 expanders differing from one another only by about twice the value of n (187 and 370 rpm, Table 2). The temperature curves in the dependence on the relative time τ/t practically coincide. At a higher rotation frequency the methane temperature is slightly higher, and the maximal difference is a few tenths of a degree at the instant of time corresponding to the onset of condensation.

We have calculated the change with time in the methane parameters in methane and air expanders [3] in which, all other technical characteristic remaining unaltered, the cylinder diameters differ more than twice (d = 42 and 110 mm, Table 2). For these expanders, the dependences of the calculated values of the temperature, supersaturation, heat release, and increment of the number of nuclei in a unit volume on the relative time of the piston stroke, respectively, coincide.

An analysis of the influence on the condensation process of the stroke length of the piston has been performed. To this end, for the methane expander [3] and the DSD-5 [6] and MDKA 500–70/5 [5] expanders (Table 2), in the calculations we varied the relative value of the piston stroke at the instant the filling of the cylinder with the gas ends. In the calculations, we used values of C = 0.20, 0.25, and 0.30, keeping a = 0.25. For each of the considered expanders, at equal initial state parameters, as the C value increases, the temperature at the end of the piston stroke towards expansion increases. This is due to the fact that the process of methane expansion and, therefore, the temperature drop begin later in time. As a result, nuclei are formed later; however, the drops grown from them are larger. Such a feature of the condensation process was discussed in the previous section. It should be noted that for expanders with different technical characteristics the drop diameters can differ more than twice. The possible coagulation of drops, which can lead to a considerable increase in their diameters, was not considered in the calculations.

Analysis of the Influence of Initial Parameters on the Working Process in the Expander. Let us consider the operation of the expander with a wider range of values of the initial parameters. The inlet pressures were taken to be equal to 2, 3, 4, and 5 MPa, the initial temperatures at each p_0 were chosen so that the input entropy values were varied from 3.5 to 3.65 kJ/(kg·K), and at the inlet to the expander the methane parameters were always in the region of dry vapor. Calculations have been performed for the methane expander [3] in the cases where only the condensation heat release is taken into account and where the working process is simultaneously influenced by the condensation, friction, and external heat inflows at $\eta_{ad} = 0.81$. For the variants considered, Figure 3 shows the influence of the initial parameters on the liquefaction coefficient. Analysis has shown that at a given pressure at the inlet to the expander an increase in T_0 leads to a delay in the onset of condensation in the expander and a decrease in the liquefaction coefficient. The delay in the onset of condensation is due to the fact that the phase transition parameters decrease, which can been seen in the *p–H* diagram (see Fig. 1). The friction and external heat inflows decrease considerably the liquefaction coefficient, and under certain conditions at the inlet condensation may not begin at all, as was discussed above.

Conclusions. Summarizing the foregoing, it may be noted that the proposed method of calculating the working process in a reciprocating expander in the presence of condensation makes it possible to elucidate the influence of various factors on the character of change with time in the parameters of a vapor-liquid medium. The given approach also permits simulation of the gas expansion in the presence of noncondensable mixtures, e.g., nitrogen in the natural gas consisting mainly of methane. The corresponding calculations have shown that no appreciable changes in the process of natural gas condensation take place.

This work is a part of the State complex scientific investigations "Energy safety."

NOTATION

$A = (k-1)/k$; a, value of the relative dead space of the cylinder; B, heat release in a unit volume, J/m^3; C, value of the relative stroke of the piston at the instant the filling of the cylinder with the gas is finished; d, cylinder diameter, m; H, enthalpy, kJ/kg; k, adiabatic index of ideal gas; K_{liq}, liquefaction coefficient, %; n, rotation frequency of the shaft, rpm; $Nu = \alpha\delta/\lambda_v$, Nusselt number for a drop; N_d, number of drops in a unit volume, m^{-3}; ΔN_n, increment of the number of nuclei in a unit volume, m^{-3}; p, pressure, MPa; Q, parameter in the calculation of the growth rate of a drop, kg/(m·sec); r, specific heat of the liquid–vapor phase transition, kJ/kg; S, entropy, kJ/(kg·K); S_{sup}, supersaturation value; s, piston stroke, m; T, temperature, K; t, total time of the piston stroke towards expansion, sec; α, heat transfer coefficient, W/(m^2·deg); δ, diameter (of a nucleus, a drop), m; η, efficiency; λ_v, heat conductivity coefficient of vapor, W/(m·K); ρ, density, kg/m^3; τ, time, sec; $\Delta\tau$, time of one step, sec. Subscripts: 0, initial value; 1 and 2, inlet to the zone and outlet from it; ∞, at a large distance from the drop; ad, adiabatic process; liq, liquid; n, nucleus; d, drop; v, vapor; eff, effective value corresponding to the real gas; sup, supersaturation state.

REFERENCES

1. A. A. Startsev, K. Z. Bochaver, V. I. Ivanov, and D. Z. Brodskaya, *Liquefaction of Methane* (*Review of the Foreign Literature*) [in Russian], VNIIOENP, Moscow (1966).
2. K. M. Aref'ev, O. V. Belyaeva, A. Zh. Greben'kov, T. A. Zayats, and A. A. Mikhalevich, Modeling of gas cooling and condensation in reciprocating expander, *Inzh.-Fiz. Zh.*, **77**, No. 5, 52–59 (2005).
3. L. G. Kuznetsov and A. L. Gorbenko, Influence of the heat exchanger in the stage on the characteristics of a reciprocating expander, *Vestn. Mezhdunar. Akad. Kholoda*, Issue 1, 12–14 (2000).
4. U. Setzmann and W. A. A. Wagner, New equation of state and tables of thermodynamic properties for methane covering the range from the melting line to 625 K at pressures up to 1000 MPa, *J. Phys. Chem. Ref. Data*, **20**, No. 6, 1061–1151 (1991).
5. I. K. Prilutskii, A. N. Bessonnyi, and A. I. Prilutskii, Gas expansion-compression aggregates on opposite bases, *Kompressorn. Tekh. Pnevmatika*, No. 6, 34–37 (2004).
6. D. L. Glizmanenko, *Production of Oxygen* [in Russian], Khimiya, Moscow (1972).