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ENSURING ECOLOGICAL AND FIRE SAFETY DURING THE OPERATION OF MOTOR VEHICLES WITH PISTON PNEUMATIC AND CRYO ENGINES WHICH USING THE NITROGEN AS WORKING BODY

In the study, the purpose of which is to improve the mathematical apparatus based on the modified thermodynamic theory of disturbances for describing the thermophysical characteristics of nitrogen in the gaseous and liquid states as the working fluid of fire-safe and environmentally safe motor vehicles with piston pneumatic or cryoengines, a mathematical model was suggested to describe for describing the thermodynamic properties of gaseous and liquid of nitrogen, which is intended for the development of a new type of fire-safe and environmentally efficient vehicle with a piston pneumo- or cryoengine and its application is illustrated. The object of the study is the thermophysical characteristics of nitrogen in a liquid or gaseous aggregate state, as a working fluid of fire-safe and eco-safe motor vehicles with a piston pneumatic or cryoengine. The subject of the research is a mathematical apparatus based on the modified perturbation theory for describing the thermophysical characteristics of nitrogen in gaseous and liquid states. The scientific novelty of the research results is that a mathematical apparatus based on a modified thermodynamic theory of disturbances has been improved for a comprehensive description of all thermophysical characteristics of nitrogen, which is in both liquid and gaseous aggregate state, in terms of reducing calculation time and reducing the error of obtaining thermophysical characteristics compared to reference and experimental data. The practical significance of the research results is that the improved mathematical apparatus is marketable for providing accurate information to the composition of the initial data set in studies on the use of nitrogen in various aggregate states as the working fluid of fire-safe and eco-safe motor vehicles with a piston pneumatic or cryoengine.

***Key words:** thermophysical properties; nitrogen; phase diagram; mathematical model; environmental protection technologies; environmental safety; power plants; piston engines; pneumatic engine; cryoengine.*

Relevance of the study

In previous studies, the authors improved the thermodynamic theory of disturbances and applied a mathematical model based on it to describe the thermodynamic characteristics of traditional (petroleum origin) and alternative types of motor fuel, including biodiesel and hydrogen, in different aggregate states – liquid and gaseous [1– 7].

The description of the thermodynamic parameters of nitrogen as a working fluid of piston-type pneumatic and cryoengines for motor vehicles in the first approximation was carried out in the article [8].

In addition, the research of the author's team on the applicability of alternative fuels (AF) at power plants (PP) with a reciprocating internal combustion engine (RICE) and related aspects of ecological safety (ES) is presented in [9,10]. It is possible to overcome the residual ES factors, in particular, the emission of legislative regulated pollutants in the flow of exhaust gases (EG) of RICE, by to the using the appropriate executive devices of environmental protection technologies (EPT), such as particulate matter filters (DPF) [11]. The effectiveness of the application of such measures to ensure the legislative established level of ES indicators of the exploitation of such PP can be complexly assessed using the developed index of the DPF effectiveness [12]. At the same time, it is equally important to ensure the disposal of solid and liquid combustible waste [13], and solid waste from the burning of fossil fuels – coal, masute [14], as well as from the burning of waste of biological origin [15].

In the modern world, there are several ecological problems, the primary sources of which are PP with RICE, among which, given the trends in the development of the energy market, the depletion of natural resources – raw materials for the production of motor fuels – is of particular importance [1,3,4]. This problem leads to the active development of alternative energy, including the production of alternative types of motor fuel [1,2], which entails a whole set of related problems of the scientific and technical plan, in particular regarding the criteria-based assessment of the fuel and ecological efficiency of such conversion [9,10], adaptation of the diesel engine to convert it to consumption of alternative or mixed motor fuel and research of the performance of the diesel engine on such fuels [11,12], etc. A separate independent direction of research and an integral component of the mentioned research works is the determination of the properties of various types of motor fuels, in particular thermophysical ones [1,2]. The results of determining such characteristics are also suitable for use in research on providing ecological, fire, and explosion safety in the processes of processing raw materials into motor fuel and its storage [13–15]. This direction of research makes it possible to postpone the transition planned in the countries of the European Union to the complete replacement of the PP with RICE by motor vehicles with a hybrid engine drive or electric vehicles [9].

In view of the above considerations, we can draw an unequivocal conclusion that the chosen topic of research, the results of which are presented in the article, is relevant, especially from the perspective of solving the problems of the post-war economics reconstructing of our country.

These studies will be especially useful for ensuring the operation of firefighting equipment units and emergency rescue vehicles with RICE of units of the State Emergency Service of Ukraine both during times of armed aggression and during the post-war reconstruction of the economics and infrastructure of our country, which additionally characterizes the relevance of the study.

The purpose of the study is to improve the mathematical apparatus based on the modified thermodynamic theory of disturbances to describe the thermophysical characteristics of nitrogen in gaseous and liquid states as the working fluid of fire-safe and eco-safe motor vehicles with a piston pneumatic or cryoengine.

The object of the study is the thermophysical characteristics of nitrogen, which is in a liquid or gaseous aggregate state, as a working fluid of fire-safe and eco-safe motor vehicles with a piston pneumatic or cryoengine.

The subject of the study is a mathematical apparatus based on the modified perturbation theory for describing the thermophysical characteristics of nitrogen in gaseous and liquid states.

Research methods. Analysis of scientific and technical, reference, normative, patent literature, modified scheme of thermodynamic disturbance theory, analysis of experimental data, method of least squares.

The objectives of the study are as follows:

1. Analysis of literary sources by research topic.

2. Improvement of the mathematical apparatus of the modified thermodynamic perturbation theory for the case and adjustment of its parameters for the case of nitrogen.

3. Obtaining the results of calculating the thermodynamic characteristics of nitrogen, their illustration and analysis.

This study was carried out as part of the implementation of the Scientific research work «Development of a methodology for complex assessment of the impact of exploitation and use of special equipment on the environment in conditions of military aggression» (State registration № 0124U000374, 01.2024–12.2026).

Analysis of researcheas and publications

The need to optimize the PP and energy recovery in the vehicle has been due for a long time, but in many ways it was limited on the one hand by the inertia of vehicle manufacturers, and on the other – by the insufficient technological level of development of environmentally friendly, fire-safe and sufficiently capacious energy accumulators and recuperators. However, to date, a number of environmentally friendly and fire-safe engines have been developed [1,8,16,17], the design of which is constantly being improved.

Air or nitrogen is used as the working fluid in such engines. In [18] it is shown that the development of pneumatic and cryotransport is promising, technically feasible and economically justified.

When considering the problems associated with the creation and application of such PP in transport, it is necessary to have reliable data on the thermodynamic characteristics of the working fluid in liquid and gaseous states.

Works [19,20] provide an overview of existing modelling methods for calculating thermodynamic properties of substances. It is shown that these methods of calculations provided acceptable results for certain thermodynamic characteristics in limited regions of states, however, in general, they turned out to be unsatisfactory, since for a set of properties, the errors of their description significantly exceeded the experimental errors.

Reference materials that reflect some of the thermodynamic characteristics of nitrogen known from experiments and used in the mathematical model improved in this study are given in sources [21–23].

Research on the features of the design and working process of cryogenic piston engines with nitrogen as a working medium are relevant [24], pneumatic piston engines are considered as promising sources of mechanical energy in buses [25], in some PP nitrogen as a working medium is exclusively in a liquid state [26], therefore, the prospects of cryogenic piston engines are currently quite defined [27], while important issues are the flow of phase transformations of cryogenic nitrogen [28], which is an integral part of engine systems for thermal energy storage [29], including turbine units [30] and piston engines [31] on cryogenic nitrogen, as well as pneumatic piston engines [32], including hybrid PP based on diesel RICE [33] and with EG recirculation [34], or Stirling engine [35], with systems of direct injection of the working medium [36], in particular cryogenic refrigerant [37], and injection of nitrogen into water under normal [38] and supercritical pressure [39] in such PP with evaluation of thermal effects [40].

Statement of the problem and its solution

This state of the problem necessitated the development of modern statistical-mechanical methods for describing the properties of molecular substances that use a minimum of initial data and parameters. The research is devoted to the application of the original modified scheme of the thermodynamic perturbation theory (TPT) [20] to describe the properties of nitrogen, in particular the isobaric heat capacity.

The free energy $F = N \cdot f$ of a system of N particles interacting with the help of the initial potential $u(r)$ at temperature T and particle number density $\rho = N / V$ has the form

$$\beta \cdot f = \beta \cdot f_0 + \rho^* \cdot (I_1 + I_2 / T^*) / T^* + \dots , \quad (1)$$

where $\beta = 1 / (k \cdot T)$; $\rho^* = \rho \cdot \sigma^3$ – dimensionless (reduced) density; I_1 and I_2 – group integrals of the TPT of the 1st and 2nd orders, respectively; k – Boltzmann's constant. The value f_0 represents the specific (per particle) free energy of the TC system:

$$\beta \cdot f_0 = \psi(T^*) + \ln \rho^* + \eta \cdot (4 - 3 \cdot \eta) / (1 - \eta)^2, \quad (2)$$

where $\psi(T^*)$ – temperature function in the ideal gas part f_0; $\eta = (\pi / 6) \cdot \rho_0^*$; $\rho_0^* = \rho \cdot d^3 = \xi^3 \cdot \rho^*$, d – TC diameter.

The advantages of the TPT scheme are, in particular, the rapid convergence of series of type (1) and the significant simplification of calculations.

The thermodynamic properties of nitrogen are obtained on the basis of the free energy surfaces $f(T,V)$ or $F(T,\rho)$ calculated according to (1) using standard thermodynamic ratios. The initial stage of calculating the properties of substances is the determination of their density D. For the two-phase region, the density of the liquid D_L and vapor D_V phases of substances on the saturation line is determined from the conditions of equality of pressures and chemical potentials of the phases:

$$\begin{cases} p(D_L,T) - p(D_V,T) = 0; \\ \mu(D_L,T) - \mu(D_V,T) = 0, \end{cases} \quad (3)$$

and the substance density $D(p,T)$ [in kg/m^3] in the single-phase region in the thermodynamic state p [in MPa] and T [in K] is from the equation

$$p(D,T) - p = 0 . \quad (4)$$

We will give expressions for the main properties.

Pressure $p = \tilde{P} T^* \rho^* z$.

Compressibility factor $z = 10^3 p / RTD$

$$z = 1 + 2\eta \frac{2-\eta}{(1-\eta)^3} + \chi_1[i+1]. \quad (5)$$

Free energy $F = RT(\beta f)$

$$\beta f = \beta h_0 - s_0 - 1 - \ln z_N + \eta \frac{4-3\eta}{(1-\eta)^2} + \chi_1[1] + \chi_2[1]. \quad (6)$$

Gibbs energy $G = RT(\beta\mu)$ ($\mu = f + z/\beta$ – chemical potential)

$$\beta\mu = \beta h_0 - s_0 - \ln z_N + \eta \frac{8 - 9\eta + 3\eta^2}{(1-\eta)^3} + \chi_1[i+2] + \chi_2[1]. \quad (7)$$

Isochoric heat capacity $C_v = Rc_v$

$$c_v = c_{p_0} - 1 - \chi_1[k(k+1)] - \chi_2[j(j+1)]. \quad (8)$$

Isobar heat capacity $C_p = Rc_p$

$$c_p = c_v + \rho^* T^* \beta_T^* \begin{Bmatrix} 1 + 2\eta \dfrac{2-\eta}{(1-\eta)^2} - \\ -\chi_1[(i+1)k] \end{Bmatrix}^2 . \quad (9)$$

Here $\eta = 0{,}4177\,\rho^*$, $\rho^* = D/\tilde{D}$, $T^* = T/E$, $p^* = p/\tilde{P}$, $\tilde{D} = M/(N_A\sigma^3)$, $E = \varepsilon/k$, $\tilde{P} = RE\tilde{D}$, $\beta_T^* = \tilde{m} \cdot \beta_T$ – given coefficient of isothermal compression [20]. The values are expressed in the following units: gas constant R – kJ/(kg·K); pressure p, parameter $\tilde{P}$ – in MPa; D – in kg/m^3; T, E – in K; β_T – in 1/MPa; F, G – in kJ/kg; C_p, C_v – in kJ/(kg·K). For nitrogen E = 97,55 K, σ = 3,5996·10^{-10} m [21], $\tilde{D}$ = 997,38 kg/m^3, $\tilde{P}$ = 8,877 MPa, R = 0,2968 kJ/(kg·K).

In expressions (5)–(9) $z_N = 10^3 p_{st}/RTD$ is the normalization function for the standard pressure $p_{st} = 0{,}101325$ MPa, and the values h_0, c_{p0}, s_0 are the specific (per molecule) enthalpy, isobaric heat capacity, and entropy in the ideal gas state.

The Passat–Danner expressions were used for the determination of h_0, c_{p0}, s_0:

$$\begin{cases} \beta h_0 = 4{,}1868 \begin{pmatrix} A + Bt + Ct^2 + \\ + Dt^3 + Et^4 + Ft^5 \end{pmatrix} \Big/ RT + \beta h_0^0, \\ s_0 = 4{,}1868 \begin{pmatrix} B \ln t + 2Ct + 3Dt^2/2 + \\ + 4Et^3/3 + 5Ft^4/4 + G \end{pmatrix} \Big/ R + s_0^0, \\ c_{p_0} = 4{,}1868 \left(B + 2Ct + 3Dt^2 + 4Et^3 + 5Ft^4 \right) / R, \end{cases}$$

where $t = 1{,}8T^*$, reference constants $h_0^0 = s_0^0 = 0$, and the used references, parameters and limits of applicability are given in the paper [22]. Expressions (5)–(9) for the main thermodynamic characteristics are easily translated into computer language and do not contain fitting parameters or empirical correlations. Calculations of thermodynamic properties (isobaric heat capacity) were performed on the basis of these expressions along the liquid–vapor equilibrium lines from the triple point to the critical point and are presented in Fig. 1. It can be seen that the ideal gas approximation for heat capacity is rough and does not describe the observed temperature dependences.

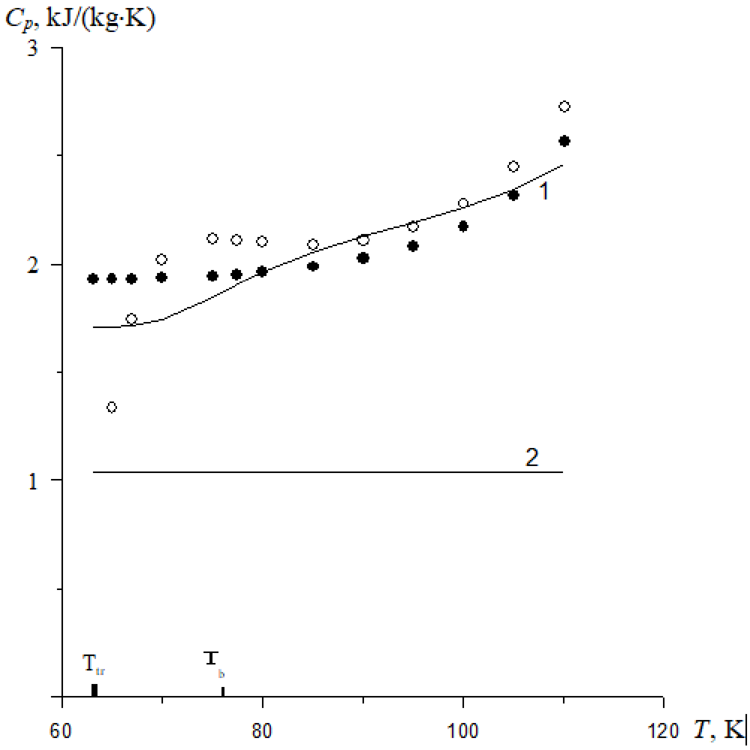

Fig. 1. Thermal capacity of average nitrogen C_p on the line of equal nitrogen-vapor: 1 – development according to the MTD scheme; 2 – ideal gas (C_p = 1.0388 kJ/(kg K); ● [22] and ○ [23] – experimental data

Conclusions

The analysis of the obtained results shows the possibility of successful application of strict statistical-mechanical methods to describe the properties of molecular systems in different phase states. The proposed calculation method makes it possible to obtain thermodynamic characteristics of liquid and gaseous nitrogen, which are used for the development of promising types of fire-safe and environmentally friendly engines for vehicles.

Scientific novelty of the results of the study.

The mathematical apparatus based on the modified thermodynamic theory of disturbances for the comprehensive description of all thermophysical characteristics of nitrogen, which is in both liquid and gaseous state, has been improved, in terms of reducing the calculation time and reducing the error of obtaining thermophysical characteristics compared to reference and experimental data.

Practical significance of results of the study.

The improved mathematical apparatus is suitable for providing accurate information to the composition of the initial data set in research on the use of nitrogen in various aggregate states as a working fluid of fire-safe and eco-safe motor vehicles with a piston pneumatic or cryoengine.

Anknoligments

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ЗАБЕЗПЕЧЕННЯ ПОЖЕЖНОЇ ТА ЕКОЛОГІЧНОЇ БЕЗПЕКИ ПРИ ЕКСПЛУАТАЦІЇ АВТОТРАНСПОРТУ З ПОРШНЕВИМИ ПНЕВМО- ТА КРІОДВИГУНАМИ, ЯКІ ВИКОРИСТОВУЮТЬ АЗОТ ЯК РОБОЧЕ ТІЛО

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У дослідженні, метою якого було вдосконалення математичного апарату на основі модифікованої термодинамічної теорії збурень для описання теплофізичних характеристик азоту в газоподібному та рідинному станах як робочого тіла пожежобезпечних та екобезпечних автотранспортних засобів з поршневим пневмо- або кріодвигуном, запропоновано й описано математичну модель для опису термодинамічних властивостей газоподібного та рідкого азоту, яка призначена для розробки нового виду пожежобезпечного та еколігочно ефективного транспортного засобу з поршневим пнемо- або кріодвигуном та проілюстровано її застосування. Об`єктом дослідження є теплофізичні характеристики азоту, що перебуває в рідинному чи газоподібному агрегатному стані, як робочого тіла пожежобезпечних та екобезпечних автотранспортних засобів з поршневим пневмо- або кріодвигуном. Предметом дослідження є математичний апарат на основі модифікованої теорії збурень для описання теплофізичних характеристик азоту в газоподібному та рідинному станах. Наукова новизна результатів дослідження полягає в тому, що вдосконалено математичний апарат на основі модифікованої термодинамічної теорії збурень для вичерпного описання всіх теплофізичних характеристик азоту, який перебуває як у рідинному, так і в газоподібному агрегатному стані, у частині зменшення часу розрахунку та зниження похибки отримання теплофізичних характеристик порівняно з довідниковими та експериментальними даними. Практичне значення результатів дослідження полягає у тому, що вдосконалений математичний апарат придатний для надання точної інформації до складу набору вихідних даних у дослідженнях щодо використання азоту в різних агрегатних станах як робочого тіла пожежобезпечних та екобезпечних автотранспортних засобів з поршневим пневмо- або кріодвигуном.

Ключові слова: теплофізичні властивості; азот; фазова діаграма; математична модель; технології захисту навколишнього середовища; екологічна безпека; енергоустановки; поршневі двигуни; пневмодвигун, кріодвигун.