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In memory of V. F. Chekurin

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The purpose of the research article is to study the contribution of V. F. Chekurin to the development of science through a comprehensive and objective analysis of the publications of the author, his colleagues and co-authors. In the creative heritage of V. F. Chekurin, it is proposed to single out three areas of his works: semiconductors, pipeline gas dynamics, and an elasticity problem. It is shown that set of works by V. F. Chekurin can be called Chekurin's theory of pipeline gas dynamics. It is recommended to be used for pipelines condition monitoring. Verification of numerical modeling results according to the RR criterion showed that among the tested models, the model is suitable if $RR < 1$. This proves that the Chekurin–Khymko model can be registered in Data Base of Geospatial Objects. The variation method of homogeneous solutions is proposed for the evaluation of residual stresses formed in cylindrical bodies.

Keywords: *Chekurin's theory of Tomography Stresses in Solids, Chekurin's Pipeline Gas Dynamics Theory, variation method for solving inverse problems, Chekurin–Postolaki's method of nondestructive testing, Chekurin–Khymko's numerical model.*

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1. Review of Chekurin's works

Chekurin's works on semiconductors. In the article [1], there was first confirmed that due to the research of V. F. Chekurin, one can detect the relaxation of surface energy and the Benedix effect in semiconductors which can be assessed as a scientific discovery. For publications [2, 3] and other works on semiconductors, the authors Y. V. Stadnyk, V. A. Romaka, V. F. Chekurin et al. were awarded the title of laureate of the prize named after M. M. Krylov of the Presidium of the National Academy of Sciences of Ukraine.

The first two works were on tomography, the first of which [4] defines the variation method, and the second [5] is about the approach to solving the stress state tomography problems of elastic solids. In [6], the theory of acoustic tomography of stresses in solids was developed. Based on these works, in the article [7] a model is developed. This model can be used for developing mathematical methods for polarized-optical computational tomography of stress-strained states of dielectric solids.

The article [7] mentions for the first time the photoelasticity phenomenon, which in combination with the tomographic approach, will allow the creation of a powerful method of non-destructive testing of the stress-strain state of solid dielectrics.

The variation method for solving the inverse problem of determining the residual stresses in the vicinity of a flat joint of dissimilar materials has been developed based on the work [4, 8]. An example for determining of residual stresses with non-destructive methods from [4] to solve the inverse problems is given.

Since the information of the empirical data obtained by the magnetoelastic method is insufficient to restore the distribution of incompatible deformations in the weld zone in its entirety, a mathematical model [4] was used. A well-known model [4] is used to take into account the residual stresses and formulate the direct problem.

The mathematical model [7] was used to formulate the inverse problem, in which incompatible deformations are concentrated on the plane separating the two semi-boundless cylindrical shells. The solution of the inverse problem in comparison with the solution of the corresponding direct problem has been studied with the use of the method of computational experiments [9]. We will call the described approach the Chekurin–Postolaki's approach to nondestructive testing.

A macroscopic model for thermoelasticity of semiconductors, developed with the use of irreversible thermodynamic formalism, is discussed. The model describes coupled mechanical, thermal, electrophysical, and electromagnetic processes in homogeneous many-valley semiconductors doped by impurities of different types. The model is grounded upon the approach of interpenetrated continuums. For accounting for the lack of local equilibrium between the subsystems, the principle of local thermodynamic equilibrium was applied in the model to each continuum separately.

The work [10] summarizes the results of all research articles described above. This work should be recognized as the highest achievement of V. F. Chekurin.

Theory and practice of pipeline gas dynamics. In the conceptual work of V. F. Chekurin [15], for the first time in pipeline gas dynamics, it was required to take into account not only the mass balance (as usual) but also the momentum and energy balances.

A number of works by V. F. Chekurin and O. M. Khymko [16–22] develop the theory of pipeline gas dynamics and its applied aspects.

In the work [23], unsteady processes of isothermal natural gas flow, emerging in a long pipeline when there is a switching-over from one stationary process to another stationary process, have been considered. The one-dimensional system of gas dynamics equations is used for that purpose. It includes equations for conservation of mass and momentum, which were proposed in the concept article [15]. The famous work [23] is discussed in more detail in Section 2 of this article.

Works [19–22] are aimed at forming the resulting work [25], which became part of a collective monograph published by Springer. The model of the software system for monitoring the integrity of the linear part of a gas main pipeline is considered. The pipeline is considered to be a linear structure formed by series-connected compressor stations and sections of the linear part. The structure model of a section consists of sequentially connected line and nodal elements. The nodal elements represent the technological objects of the linear part, which create small pressure drops between their inputs and outputs.

Fundamental work [24] has only one reference to its own publication: it is the glanced work [23], the Chekurin–Khymko's numerical model.

The work [18] is discussed in Section 3 of the article.

Elasticity problem. An approach for solving the axisymmetric biharmonic boundary value problems for a semi-infinite cylindrical domain was developed in the paper [26]. To solve the formulated biharmonic problems the method of least squares on the boundary combined with the method of homogeneous solutions was used. The developed approach can be used particularly to solve the axisymmetric elasticity problems for cylindrical bodies.

Mathematical models and methods for determination of axisymmetric residual stresses in a finite cylinder are considered in [27]. A method based on the variation method of homogeneous solutions is developed for solving the direct problem. The inverse problem solving for residual stresses determination on the base of empirical data obtained by a photoelasticity method is suggested. The results presented in [26] can be used for the development of methods and means for nondestructive testing.

An axially symmetric problem for a hollow cylinder with unloaded bases is considered in the work [29]. The problem is reduced to a biharmonic equation with corresponding boundary conditions. The quantitative studies have confirmed the good convergence of the method.

The work [30] considers the problem of determination of axisymmetric residual stresses caused by incompatible residual strains in a circular cylinder of finite height. The variation method of homogeneous solutions from [25, 28] was used. Authors also perform the numerical analysis of residual stresses formed in a solid for two given distributions of incompatible strains depending on the radial coordinate.

The proposed approach can be used for the evaluation of residual stresses formed in cylindrical bodies in the course of their heat treatment.

A horizontally layered elastic structure containing a homogeneous porous layer saturated partly with gas and partly with water is considered [31]. It was established that the wave field pattern on the free surface of the structure is dependent on the amount of gas accumulated in the porous layer. Quantitative measures relating the wave field parameters on the structure's free surface and the amount of gas accumulated in the porous layer are introduced. The innovative results can be used to develop distance methods for accounting for the amount of natural gas accumulated in underground gas storage. The problem of porous media is also considered in [32, 50].

2. Analysis of numerical modeling in Chekurin's Gas Dynamic Theory

Three boundary value problems formulated for the gas pipeline system define three models for control of the transient processes [18]. The problems differ by the boundary (control) functions imposed at the ends of the gas pipeline. A unified model for the control functions is introduced. According to this model, such a function is defined by four real parameters. That restricts the class of control functions by the smooth ones monotonically varying from the value characteristic for the first stationary regime to the other one specific for the second stationary regime. The transient processes realized with the use of the models for various values of control parameters are analyzed numerically in this article.

Application of the considered mathematical models and obtained results of conducted case-studies for planning the transient regimes of pipelines operation are discussed in the paper. This practical orientation of the work requires especially careful verification of models, the results of which are given in Table 2 cited from the work.

Computing experiments are the final stage of the research triad. Table 2 of the work [23] shows the results of numerical simulation of transient processes from stationary regime 1 to stationary regime 2.

Table 1. The functionals of the transient processes (Table 2 of work [23]).

Algorithm	Direction	τ_{Tr}	$A_{\mathsf{Tr}}, 10^3$	M_{Tr}^{in}	$\bar{j}_{\mathsf{Tr}}^{in}$	M_{Tr}^{out}	$\bar{j}_{\mathsf{Tr}}^{out}$	$\mathbf{Q}_{\mathsf{Tr}}^{\mathbf{in}}, \mathbf{10^3}$	$Q_{\mathsf{Tr}}^{out}, 10^3$
$\mathsf{BVP}_{\mathrm{I}}, \Pi_{\mathrm{I}}^1$	1–2	68.18	1.84	1.42	0.85	1.20	0.72	**1.29**	1.53
$\mathsf{BVP}_{\mathrm{I}}, \Pi_{\mathrm{I}}^2$	1–2	53.84	1.51	1.18	0.90	0.95	0.72	**1.28**	1.59
$\mathsf{BVP}_{\mathrm{I}}, \Pi_{\mathrm{I}}^3$	2–1	66.22	1.66	1.02	0.63	1.24	0.76	**1.63**	1.33
$\mathsf{BVP}_{\mathrm{I}}, \Pi_{\mathrm{I}}^4$	2–1	49.43	1.21	0.71	0.58	0.94	0.77	**1.71**	1.29
$\mathsf{BVP}_{\mathrm{III}}, \Pi_{\mathrm{I}}^1$	1–2	125.75	3.31	2.45	0.80	2.23	0.72	**1.35**	1.48
$\mathsf{BVP}_{\mathrm{III}}, \Pi_{\mathrm{III}}^2$	2–1	123.50	3.11	2.06	0.68	2.28	0.75	**1.51**	1.37
$\mathsf{BVP}_{\mathrm{II}}, \Pi_{\mathrm{III}}^1$	1–2	153.60	5.78	3.26	0.87	3.04	0.81	**1.77**	1.90
$\mathsf{BVP}_{\mathrm{II}}, \Pi_{\mathrm{II}}^2$	1–2	175.67	8.10	3.77	0.88	3.55	0.82	**2.15**	2.28
$\mathsf{BVP}_{\mathrm{II}}, \Pi_{\mathrm{II}}^3$	1–2	93.39	2.66	1.38	0.85	1.70	0.75	**1.39**	1.56
$\mathsf{BVP}_{\mathrm{II}}, \Pi_{\mathrm{II}}^4$	2–1	135.52	2.11	1.60	0.58	1.18	0.64	**1.10**	0.98
$\mathbf{BVP}_{\mathrm{II}}, \mathbf{\Pi}_{\mathrm{II}}^5$	**2–1**	**169.56**	**2.33**	**2.35**	**0.57**	**1.80**	**0.62**	**0.99**	**0.91**
$\mathsf{BVP}_{\mathrm{II}}, \Pi_{\mathrm{II}}^5$	2–1	67.31	1.70	1.05	0.64	1.26	0.76	**1.62**	1.36

Parameters Q^{in} and Q^{out} define the specific energy, expended for entering the gas into the pipeline through the inlet and delivered it into the gas transmission system through the outlet of the pipeline. Dimensionless parameters Q_{Tr}^{in} and Q_{Tr}^{out} are functionals of the transient process. They can be used to evaluate the power efficiency of the transient process by comparing them to corresponding parameters Q1 and Q2 of the stationary processes Stationar1 and Stationar2. Since the approach proposed by the authors work [23] is fully consistent with the natural principle of comparing the output of the model with the standard adopted in the RR criterion, it is acceptable and expedient to apply this criterion for verification of the results presented in Table 1.

According to the well-known criterion RR, for which there is the suitability border $RR = 1$ [33], this means that there are reliable models for transient processes. This conclusion confirms the expediency of using Chekurin's theory for the practical solution of problems.

The undeservedly forgotten RR criterion (1990) received power theoretical support in the big multidisciplinary article [34], due to the fact that it proved the principal correspondence of the RR-criterion to the fundamental Kolmogorov's Idea about informative a model to the real random process.

3. Recommendations on modernization of Gas Transmission System

The model of the software system for monitoring the integrity of the linear part of a gas main pipeline is considered [24]. The structure model of a section consists of sequentially connected line and nodal elements. The nodal elements represent the technological objects of the linear part, which create small pressure drops between their inputs and outputs.

It was first confirmed innovative approach by N. I. Samoilenko et al. (2009), based on graph theory, and named Samoilenko's Gas Pipeline Graph Model. It is followed by the monograph [35] on the adequacy of pipeline systems functional reliability models and article [36] about models and algorithms for solving problems for gas distribution systems. Two methods (basic and simplified) have been developed for dividing a pipeline network graph into subgraphs of emergency repair zones, which determine the sequence and order of graph edges that ensure its continuous connectivity. A specific example of determining the sequence and order of the edges of a pipeline network graph at the initial stage of splitting the pipeline network graph into subgraphs of the emergency repair zones is considered.

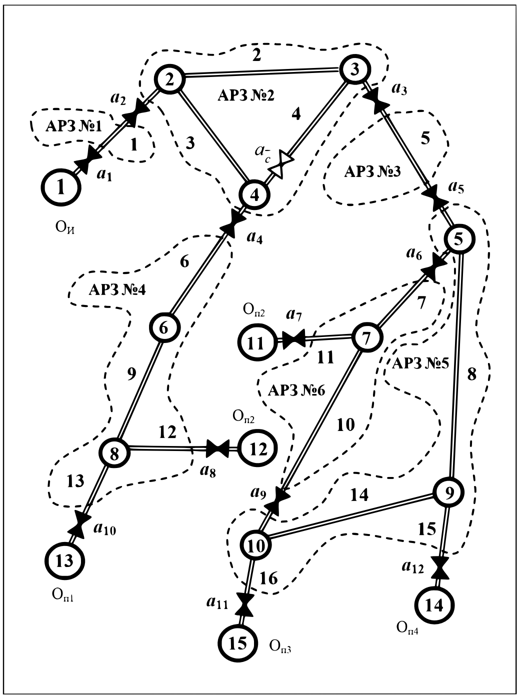

Fig. 1. Chart of dividing the original graph of the pipeline transport network into subgraphs of emergency repair zones.

A specific example of determining the sequence and ordering of the edges of a pipeline network graph at the initial stage of splitting the pipeline network graph into subgraphs of emergency repair zones is considered.

Analysis of the scheme in Fig.1 shows that under the conditions of the example, each consumer is fed by two different ARZ and has two different routes of supply of the target product (CP), which do not intersect. This indicates the maximum (one hundred percent) overhaul of the network, i.e., carrying out emergency repair or maintenance work in any area does not lead to interruption of supply of securities in the system to at least one consumer. Reliability, informative and representation of the model, its suitability for use with GIS, make this model the main cartographic component of the GTS, also suitable for registration in topographic Geospatial database.

A mathematical model of the gas transmission system is studied in the article [37]. Models of gas flows in the main technological objects, which are involved in the transportation of gas are represented. The system structure is represented in terms of graph theory. Adaptive algorithm of the gas transportation system model implementation is constructed. Real world examples of its work are presented in this article.

A comparison of these two models shows the advantage of the Samoilenko's model since it has developed methods for localizing emergency zones and solving applied problems aimed at uninterrupted gas supply to consumers with respect to the time criterion.

In the multifaceted work [24] of the authors Chekurin V., Kushnir R. et al., the following statement is given: "Mathematical models of gas motion through such elements contain ordinary time-dependent differential equations. Gas flow through the line elements is described by partial differential equations, which depend on the spatial coordinate and time". Such problems were considered by the authors Pyanylo Ya., Prytula N., Prytula M. in works [37–39]. In articles [40, 41], optimization of operational parameters of the main gas is described. In the work [42], computational experiment is considered; although it did not lead to positive results, it contributed to the success of the famous article [23].

The Chekurin–Khymko's numerical modeling [23] is the first and so far the only contender for inclusion in the state geospatial database (GeoSpatial DataBase). This problem is discussed in [43] and for the topographic level using GIS in [44].

Another quote from classic work [24]: "An object integrity control systems include sensors of informative parameters, logging systems, monitoring database, mathematical models and object integrity checking algorithms, data exchange subsystem and information security subsystem". These include the works of Kharkiv scientists Tevyashev A. D. and Dyadyun S. V. [45, 46] on the problems of monitoring and control in pipeline water supply systems. In particular, works [47–50] are focused on methods of transmitting informative parameters for the formation of a monitoring database.

4. Conclusions

Professor V. F. Chekurin obtained significant results in the field of interconnected field mechanics and physical materials science. For these and other works in the field of semiconductors, professor V. F. Chekurin received the title of laureate of the prize named after M. M. Krylov of the Presidium of the National Academy of Sciences of Ukraine.

The solution of the inverse problem in comparison with the solution of the corresponding direct problem has been studied with the use of the method of computational experiments [9]. We suggest naming the described approach by the Chekurin–Postolaki's approach to nondestructive testing.

The macroscopic model for thermoelasticity of semiconductors, developed with the use of irreversible thermodynamic formalism [10], has been published in the Encyclopedia of Thermal Stresses. This work can be recognized as the highest achievement of V. F. Chekurin.

In the conceptual work by V. F. Chekurin [15], for the first time for pipeline gas dynamics it was required to take into account not only the mass balance (as usual), but also the momentum and energy balances.

The Chekurin–Khymko's numerical model [23] is the first and so far the only contender for inclusion in the state geospatial database. The famous work included there is a numerical model named after Chekurin–Khymko.

The fundamental work [24] was published in Civil Engineering, vol. 102, Springer, Cham.

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Метою наукової статті є дослідження внеску В. Ф. Чекуріна в розвиток науки шляхом всебічного та об'єктивного аналізу публікацій автора, його колег і співавторів. У творчій спадщині В. Ф. Чекуріна пропонується виділити три напрямки його роботи: напівпровідники, газодинаміка трубопроводів та проблема пружності. Показано, що сукупність робіт В. Ф. Чекуріна можна назвати теорією газодинаміки трубопроводів його імені. Рекомендується використовувати цю теорію для моніторингу стану трубопроводів. Перевірка результатів чисельного моделювання за критерієм RR показала, що серед перевірених моделей є відповідна модель, для якої $RR < 1$. Це свідчить про те, що модель Чекуріна–Химко може бути зареєстрована в БД геопросторових об'єктів. Запропоновано варіаційний метод однорідних розв'язків для оцінки залишкових напружень, що утворюються в циліндричних тілах.

Ключові слова: *теорія Чекуріна з томографії напружень у твердих тілах, теорія газодинаміки трубопроводів, метод варіації для розв'язування зворотної задачі, метод неруйнівного контролю Чекуріна–Постолакі, чисельна модель Чекуріна–Химко.*