ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD)
Specialty 6D060400 – Physics

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SELF-CONSISTENT MODEL OF PHYSICAL PROPERTIES OF DUSTY PLASMAS

In the present dissertation work, the static and dynamic properties of dusty plasma are studied based on the proposed effective interaction potential of dust particles of finite sizes.

The relevance of the dissertation theme.

Dusty plasma, or plasma with particles of macroscopic size, called dust particles, has attracted the attention of scientists for several decades. This interest is due to the fact that dusty plasma, on the one hand, is widespread in outer space, and on the other hand, is a working fluid in technological installations. In addition, dusty plasma is intentionally created as an object of research in laboratory conditions with the aim of studying its various properties. All this leads to the fact that currently the processes occurring in a dusty plasma are intensively studied theoretically, experimentally, and also using computer simulation methods.

One of the main problems arising in connection with the problem of the implementation of controlled thermonuclear fusion – the heating and retention of high-temperature plasma – should be highlighted. The fact is that it is not possible to avoid the contact of the high-temperature plasma with the walls of the reactor and, apparently, it is completely impossible to prevent it. This contact leads to the formation of a dust component inside thermonuclear installations, consisting of the material of the first wall. The appearance of dust in the wall region immediately affects the processes of heat transfer between the first wall and plasma heated to high temperatures, which affects the process of plasma confinement, and consequently, the behavior of the dust component, its effect on the plasma and the physical properties of the material of the walls of the reactor necessitates solving an urgent problem on the study of its thermodynamic properties and electrodynamic characteristics.

The unique properties of dusty plasma are explained by the fact that dust particles in a plasma acquire a large electric charge. Moreover, strictly speaking, dusty plasma is an open system, the physical properties of which are determined by a very large number of processes and phenomena. Therefore, dusty plasma is increasingly called complex in the literature. Despite the fact that since the beginning of research on dusty plasma, significant progress has been made in understanding its behavior under various external conditions, a number of the obtained results still need a physical interpretation, which, in turn, stimulates the further development of this field.

It is generally recognized that dusty plasma will find wide practical application in the very near future, but it is still interesting in that the dynamics of dust particles can be directly recorded in an experiment using a high-speed video camera, and this makes it possible to directly test theoretical approaches developed for many charged particle systems.

Based on the foregoing, the thesis is relevant, as it is devoted to the construction of a self-consistent theory of static and dynamic properties of dusty plasma, which will allow determining such characteristics as the charge of dust particles, the potential energy of their interparticle interaction, and based on them to calculate the correlation functions and thermodynamic potentials, and also within the framework of the method of moments - dynamic structural factors and dielectric characteristics of the dust subsystem.

The purpose of the dissertation is to build a self-consistent theory of static and dynamic properties of dusty plasma, which sequentially takes into account the finiteness of the size of dust particles. This allows us to describe various collective phenomena in a unified approach, such as the spectrum of dust-acoustic waves, taking into account the recharge of dust particles in the process of their propagation.

The object of research is the dusty plasma with dust particles of finite sizes.

The subject of research is the static and dynamic characteristics of the dust component, such as the particle interaction potential, radial distribution functions, and static structural factors, thermodynamic functions, the dynamic structural factor and its moments, dispersion and attenuation decrement of dust-acoustic waves.

In order to achieve the above-stated goal, it is necessary to solve the following problems:

– to study the dependence of the charge of dust particles on the parameters of the buffer plasma;

– to construct and analyze the effective potentials of the interparticle interaction of charged dust particles of finite sizes in the plasma;

– calculate the correlation functions of dust particles by the method of integral equations (Ornstein-Zernike equation in the hyperchain approximation and its generalizations);

– determine the thermodynamic properties of the dust component of the plasma-based on the obtained correlation functions;

– using the method of moments to obtain dynamic structural factors of a strongly coupled plasma dust component, calculate the dispersion and damping decrement of dust-acoustic waves.

The main provisions for the defense:

– the interaction potential of dust particles, which takes into account the finiteness of their size in the framework of the theory of linear dielectric response, practically coincides with the Yukawa potential for small values of the screening parameter $\kappa \ll 1$, and with its growth lies systematically higher;

– the position of the first maximum on the curve of the static structural factor shifts toward lower wave numbers by ~ 10% with an increase in the coupling parameter in the range $\Gamma = 20 \div 100$ and with a decrease in the screening parameter in the range $\kappa = 1 \div 3$, and when the packing density of dust particles changes orders in the interval $\eta = 10^{-8} \div 10^{-1}$ the position of the first peak remains almost unchanged;

– the spectrum of dust-acoustic waves, taking into account the recharge of dust particles in the isothermal compressibility of a strongly coupled dust component, qualitatively changes its shape when the parameter of the density of dust packing in the interval $\eta = 10^{-9} \div 10^{-5}$ so that the presence of a maximum is replaced by a monotonic increase depending on the wave number;

– In the spectrum of dust-acoustic waves with sufficiently large coupling parameters, a roton minimum appears, the position of which corresponds to the position of the first maximum on the curve of the static structural factor, which directly confirms the Feynman hypothesis about their mutually inverse relationship. In accordance with this, the wavenumber of the roton minimum remains almost unchanged when the packing density of dust particles varies in the interval $= 10^{-8} \div 10^{-1}$.

The scientific novelty of the dissertation results.

For the **first** time in this work the author:

– In the framework of classical plasma electrodynamics, a model for the interaction of particles in a dusty plasma has been developed, taking into account the finiteness of dust particles and the phenomenon of screening of the field, which allows one to correctly take into account the boundary condition on the surface of dust particles;

– It was found that the position of the first peak on the curve of the static structural factor is practically independent of the packing density of dust particles and is determined by the coupling and shielding parameters;

– In the isothermal compressibility of a strongly coupled dust component, the processes of recharging dust particles are taken into account, which leads to a qualitative change in the behavior of the spectrum of dust-acoustic waves even for dust particles of very small sizes;

– Using the method of moments, a relationship is established between the positions of the roton minimum and the first maximum on the curve of the static structural factor.

The practical importance of the dissertation.

In the dissertation, a consistent theory of static and dynamic characteristics of the dusty plasma component with particles of finite sizes is developed. The constructed self-consistent model correctly describes the equilibrium properties of the system and can be used to calculate the equation of state and the correlation energy of the non-ideal dust component, the parameters of which correspond to various astrophysical objects, the conditions of thermonuclear fusion in the near-wall region of tokamaks, as well as experiments at the international space station. Dynamic structural factors and spectra of dust-acoustic waves can be used to diagnose the plasma medium itself.

Thus, all the above results are of both practical and theoretical importance for solving problems associated with the study of various processes occurring in dusty plasmas.

Validity and reliability of the results.

In the dissertation, well-known physical models and proven mathematical methods were used. The obtained results, based on computer simulation, are consistent with various theoretical approaches, such as the molecular dynamics method, Monte Carlo method. When applying various approaches of statistical physics of non-ideal systems, such as the method of integral equations and Monte Carlo simulation at not too high packing densities, they give well-consistent results when calculating the correlation functions with the authors of other approaches. At not too high packing densities, the Ornstein-Zernike equation in the hyperchain and basic hyperchain approximations give almost identical results on the radial distribution function.

The results are characterized by internal unity, due to the internal logic of the goals, and are reliable, as they are based on well-known and tested methods of plasma physics, developed for systems with strong interparticle interaction.

Also, the reliability and validity of the results are confirmed by publications in journals of far abroad with high impact factors and in publications recommended by the Committee for Control in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, as well as in the proceedings of international scientific conferences of near and far abroad countries.

The personal contribution of the author: the author fulfilled the research, chose the methods of investigation, solved the problems and made numerical calculations. Formulation of the problems and their discussions were made together with scientific supervisors.

Publications. The materials of the dissertation were published in 30 papers: 19 articles in peer-reviewed journals, including 5 journals from the list of CCSES MES RK and 5 journals with high impact-factor; 11 abstracts of reports were presented at international scientific conferences including 6 publications in materials of foreign conferences.

Approbation of the dissertation. The results obtained in the dissertation were presented and discussed:

– At scientific seminars of the Department of Plasma Physics, Nanotechnology and Computer Physics, KazNU al-Farabi.

– At the international conference "Actual Problems of Modern Physics" dedicated to the 75th anniversary of Academician of the NAS of the Republic of Kazakhstan Abdildin MM, Almaty, 2013;

– At the 8th international scientific conference "Modern achievements of physics and fundamental physical education", October 9-11, 2013, Almaty, Kazakhstan;

– At the international conference "Modern Problems of Physics and New Technologies", February 21-22, 2014;

– International Conference “Strongly Coupled Coulomb Systems”, Santa Fe, USA, 2014;

– 14th International Conference on the Physics of Dusty Plasmas, 26-29 May, 2015, Auburn, Alabama, USA;

– International Conference on the Physics of Non-ideal Plasmas – 15, 2015 (Almaty, Kazakhstan);

– VIII International Conference on Plasma Physics and Plasma Technology, September 14-18, 2015, Minsk, Belarus, Contributed Papers;

– 42nd IEEE International Conference on Plasma Science, 2015, Belek, Turkey;

– 42nd European Physical Society Conference on Plasma Physics, Lisbon, Portugal, 2015;

– 43rd IEEE International Conference Plasma Science, June 19-23, 2016, Banff, Alberta, Canada;

– II, III and IV International Farabi readings, 2015, 2016 and 2017. (Almaty, KazNU named after al-Farabi); as well as at the scientific seminar "Nonlinear and correlation phenomena in plasma physics" of the Faculty of Physics and Technology of KazNU named after al-Farabi;

– 9th International Scientific Conference "Modern Physics and Fundamental Physical Education", Kazakhstan, Almaty, October 12-14, 2016;

– International Conference on Strongly Coupled Coulomb Systems, 2017 (Kiel, Germany);

– 16th International Conference on the Physics of Non-ideal Plasmas – Saint-Malo, France, 2018.

Relation of the dissertation theme to the plans of scientific research. The dissertation was fulfilled in accordance with the plans of the following fundamental scientific research works (SRW) SC RK MES «Grant funding of scientific research» on the themes:

– «Investigation of the properties of dusty plasma based on the proposed model of particle interaction» (2012-2014, No. 0112PK00935, code 1129/GF);

– «Self-consistent model of static properties of dusty plasma with particles of finite sizes» (2015-2017, No. 0115PK01051, code 3120/ GF4);

– «Investigation of the dynamic and optical properties of dense Coulomb systems» (2015-2017, No. 0115PK01050, code 3119/ GF4).

Volume and structure of the thesis. The dissertation work consists of the introduction, 4 chapters, conclusion and the list of references of 178 items. It contains 125 pages of basic computer text including 92 figures and 1 table.