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PLASMA RESEARCH IN THE THERMODYNAMICS DIVISION

In this state some recent research concerning the theoretical and experimental investigations of low- and high-temperature plasmas was done. The model of LTE and non-LTE was used to descriptions of plasma conditions. The non-LTE assumptions were applied to two-temperature state of plasmas and to the ionizational nonequilibrium. The result of the research was the analysis of the transport phenomena in isotropic and anisotropic plasmas, where anisotropic was done by the external electric or magnetic fields. The experimental part of the research concerned the plasma measurement methods, particularly applied to the Klein effect, the spectroscopic methods and the laser diagnostics of plasma. Some research studied the interactions between strong magnetic field and injected gas flux to a reactor. This is the fundamental problem in controlled fission processes (the high-temperature plasma).

INTRODUCTION

Plasma is the medium in which the movement of electric charge carriers appears. This is a very general definition, suitable as well for electron gas in metal as for electrolytic solution. The gas plasma, which is a mixture of neutral particles, ions and electrons, has been the primary interest in the Thermodynamics Division for many recent years. Due to thermodynamic conditions (pressure and temperature) the plasma can be divided in different manner. According to above the weakly, partially or wholly ionized plasma can be considered, and each one can be divided into low- and high-pressure plasma. The division into low-temperature (in range of tens thousand degrees) and high-temperature plasma (in range of million degrees) is also possible. In practical technical applications only the low-temperature plasma has been utilized up to now. For instance: plasma light sources, cutting, melting and welding by plasma, protective coating and plasma chemical reactors. It seems that plasma magnetohydrodynamic generators, in which the direct conversion of heat into electric energy is realized, as well as plasma engines for propulsion of space shuttles will be technically applicable in coming years. One of prospective branches of study, concerning the interaction of plasma with solids, has already been used in designing the protective coating layer and cooling systems of space shuttles forcing their way across upper (ionized) earth's atmosphere. This short survey of possible plasma applications is very incomplete but demonstrates the wide range of interests.

All the research questions of plasma can be divided into two groups: internal problems, which appear inside the plasma generator, where the plasma is in stationary state, and external problems, where the outside generator nonequilibrium plasma relaxes to the full equilibrium state as a result of surrounding interaction. In both mentioned cases the full description of complex physical phenomena is impossible. Owing to high temperature, direct measurements of plasma parameters and functions are not possible either. Therefore, it is necessary to develop such methods of plasma description, which, by acceptable simplification of this phenomenon, could render its possible theoretic investigation.

The Thermodynamics Division carriers out investigations in which the equilibrium and nonequilibrium plasmas and their properties are analyzed by means of theory. The experimental methods for indirect measurements of plasma parameters are conducted currently as well. The following part of this paper is concerned with the last plasma research achievement of the Thermodynamics Division.

1. THEORETICAL INVESTIGATIONS

Kinetic description of plasma can be simplified by assumption that the number of interelectron collisions is negligibly small or is predominating in relation to other kinds of collisions. In the first case this plasma is weakly ionized, in the second – partially ionized. Fig. 1, taken from [1], demonstrates values of pressure and temperature which limit these models for argon plasma.

The description of ideal plasma in the state of local thermodynamic equilibrium (LTE), employing the above-described models, has been well known for a long time. Nevertheless, the numerical calculations of plasma transport coefficients are very complicated. The Thermodynamics Division performed a series of studies for the purpose of calculation of electron transport coefficients (electrical conductivity, thermal conductivity and thermodiffusion) of plasma generated from noble gases. Calculations were done for nonideal plasma in the LTE state. Nonideality of plasma is caused by Debye shielding of ions and atoms by electrons. Results of calculations for electrical conductivity of isotropic argon plasma, taken from [1], are presented in Fig. 2.

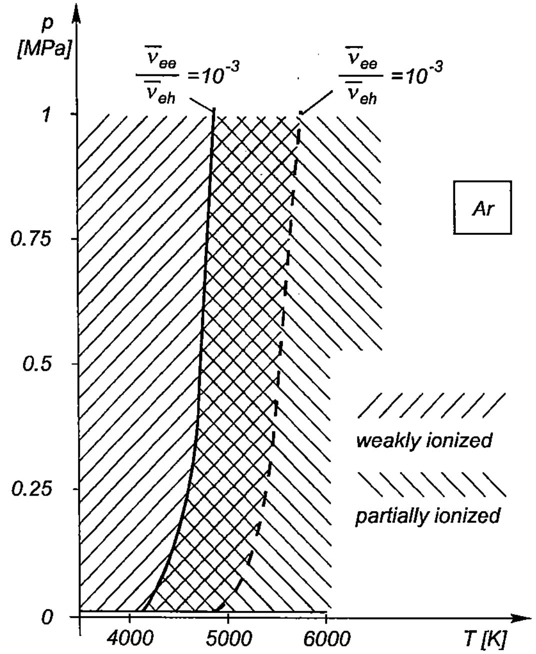

Fig. 1. The pressure and temperature limits for the partially and weakly ionized argon plasma

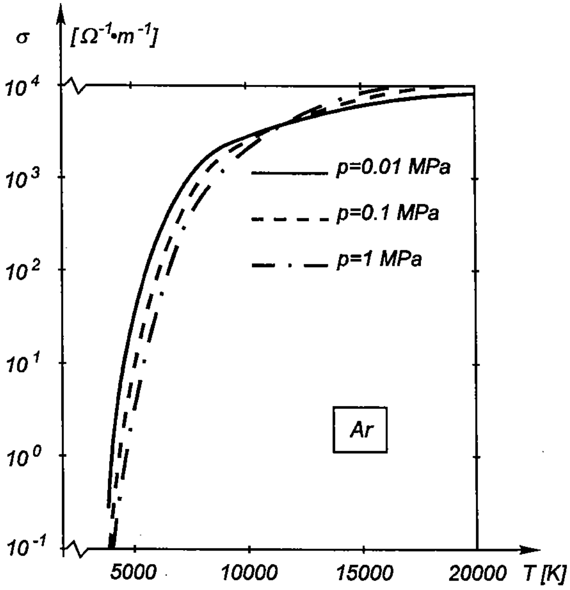

Fig. 2. Coefficient of electrical conductivity of partially ionized argon plasma vs temperature

In this series of studies anisotropic plasma was also taken into account, where anisotropy was generated by external magnetic field, as well as the RF electric field.

When the external electric field interacts with plasma, then the difference of energy between free electrons and heavy particles appears. This difference exists, because the electrons obtain the energy from electric field on the length of their mean free path, while the heavy particles accelerate only owing to collision with electrons. In sufficiently strong electric field the difference of energy is great enough for the thermal nonequilibrium (electron temperature T_e is higher than heavy particles temperature T_h) to appear in plasma. The maximum value of electric field $E_{\max}$, when the plasma is still one-temperature (in LTE state), was determined in [1] and demonstrated in Fig. 3.

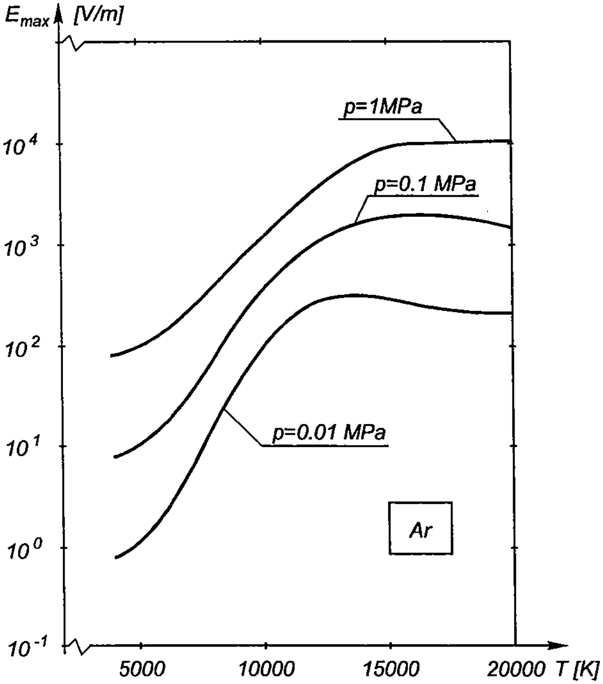

Fig. 3. Maximum values of electric field for isotropic, one-temperature argon plasma

When the thermal nonequilibrium appears, the using of LTE hypothesis is not possible to plasma description. One of the consequences of this situation is the necessity of finding a new nonequilibrium distribution function for electrons f_e, while it is no more the Maxwellian

$$f_M = \left(\frac{m_e}{2\pi kT_e}\right)^{1.5} \exp\left(-\frac{m_e C^2}{2kT_e}\right) \tag{1}$$

where C – velocity of chaotic movement of electrons.

Paper [2] presents solution of the kinetic equation in the form of the function f_e for weakly ionized argon plasma with thermal nonequilibrium caused by external electric field. When the distribution function is known, then the electron temperature may be counted from a definition

$$1.5kT_e = \int_0^\infty \frac{m_e C^2}{2} f_e 4\pi C^2 dC \tag{2}$$

In Fig. 4, taken from [2], the comparison of the shapes of non-Maxwellian function f_e is done with respect to the equilibrium function f_M (1), into which the electron temperature T_e, calculated from definition (2), has been substituted.

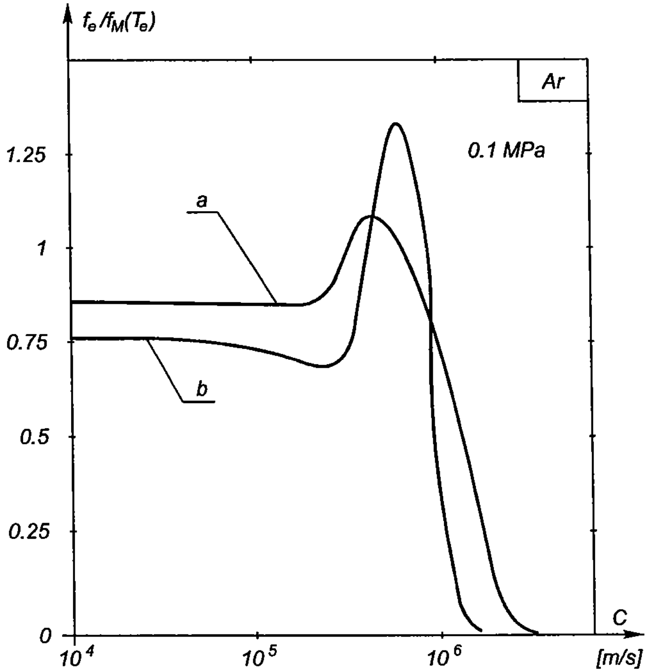

Fig. 4. Comparison of distribution functions f_e and f_M: a) E = 9 V/m, b) E = 90 V/m

Thermal nonequilibrium generates simultaneously a change of almost all plasma parameters. Fig. 5, taken from [2], demonstrates changes of the coefficients of electrical conductivity in nonequilibrium argon plasma.

Summary of the Division's research work on thermal nonequilibrium isotropic and anisotropic plasmas can be find in [3], where anisotropy is generated by crossing the electric and magnetic fields, or spatial gradient of electron density. Fig. 6, taken from [3], demonstrates the change of temperature T_e in anisotropic plasma vs angle α, where α is defined by the field vectors $\boldsymbol{E}$ and $\boldsymbol{B}$.

Populations of the levels of heavy-particles and the number density of free electrons result from radiative and collision processes of all plasma components. Total radiation rates for some transitions depend on local value of specific

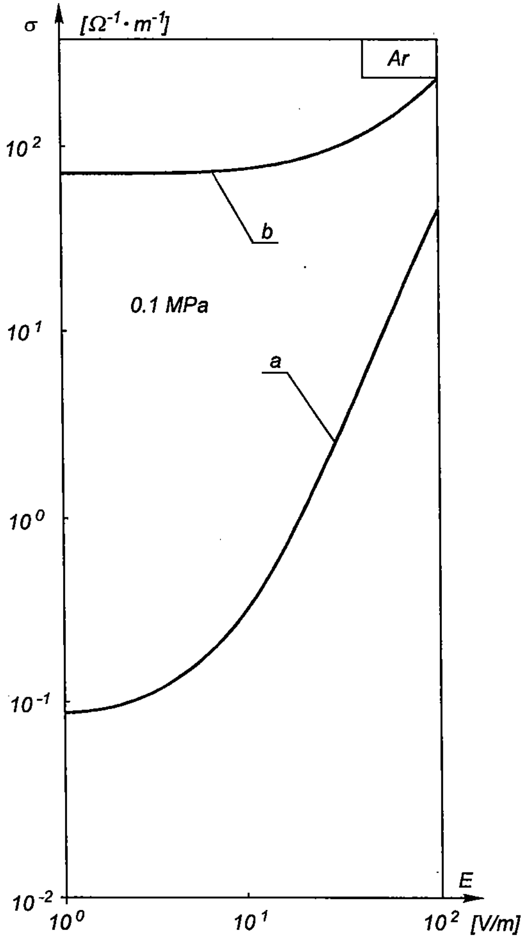

Fig. 5. Electrical conductivity in plasma with $T_e \neq T_h$: a) T = 4000 K, b) T = 6000 K

intensity. In the state of the full thermodynamic equilibrium population of excited levels is described by Boltzmann relation, mass action law for the processes of collisional ionization is transformed to Saha equation, and specific intensity of radiation is given by Planck function. In the real plasmas radiation escape always exists and it leads to the imbalance of forward and backward radiation processes rates (for example photoexcitation and spontaneous emission). This generates the ionization nonequilibrium.

A series of research concerning the plasma in the state of ionization nonequilibrium has been done in the Thermodynamics Division recently. Exemplary results of this work, taken from [4], are demonstrated in Figs. 7 and 8, where all functions and parameters of nonequilibrium plasma are referred to corresponding values of LTE plasma.

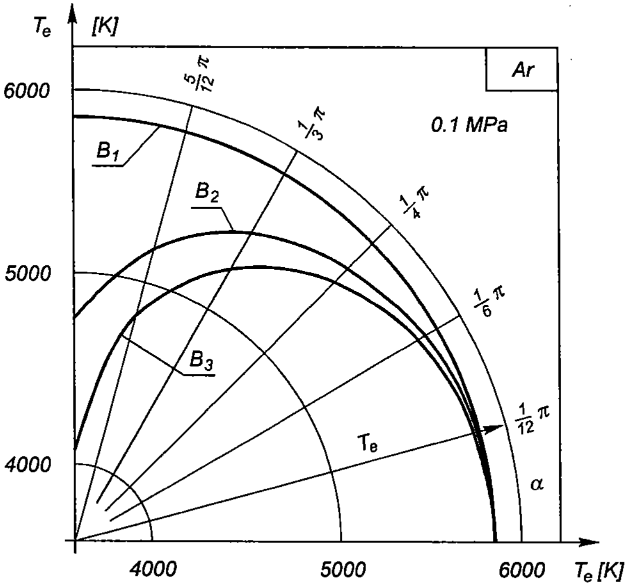

Fig. 6. Electron temperature of anisotropic argon plasma T = 4000 K, E = 90 V/m, $B_1 = 10^{-2}$ T, $B_2 = 10^{-1}$ T, B_3 = 1 T

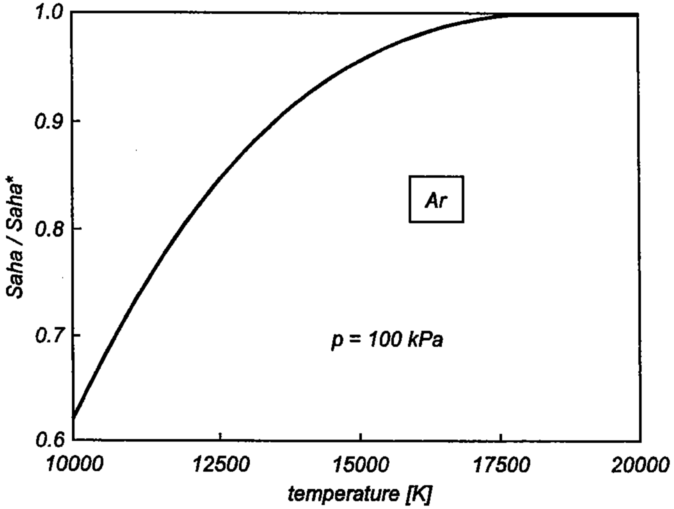

Fig. 7. Deviation from Saha equation (* denotes the LTE plasma conditions)

This short review does not demonstrate all subjects concerning the low-temperature plasma realized in the Thermodynamics Division. Popular scientific character of this paper does not permit to demonstrate the results of highly detailed investigations. Further investigations will be directed to more exact

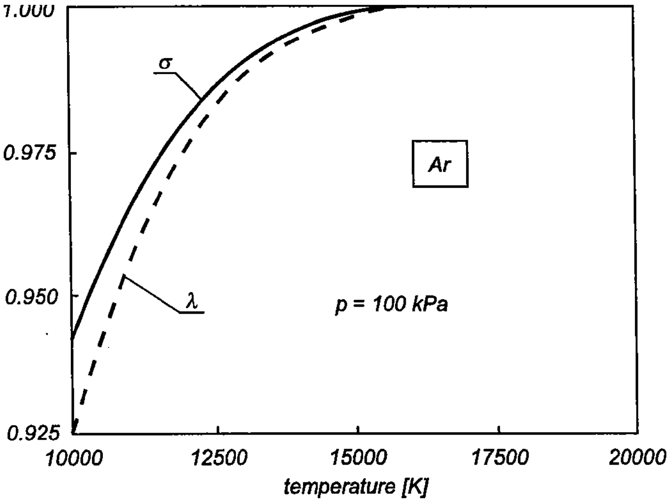

Fig. 8. Electron transport coefficients: λ – thermal conductivity, σ – electrical conductivity

recognition of nonequilibrium plasma (non-Maxwellian distribution function in partially ionized, low-pressure plasma) and to the interaction of nonequilibrium plasmas with solids (melting, covering).

2. EXPERIMENTAL INVESTIGATIONS

The experimental part of the plasma research carried out at the Institute of Heat Engineering concerned low-temperature plasmas. The first topic was strictly connected with the so-called caloroelectric effect.

As it is known, a wall placed in a plasma is charged negatively to the value defined by the so-called floating potential. If the wall is cooled below saturation temperature of a vapour of medium, which has been ionized, the potential of the wall increases. It has been shown that this effect does not occur when one deals with uncondensable vapour. When two electrodes (one cooled, the other not) are inserted in plasma, a difference of electric potential is established, being the essence of the caloroelectric (Klein) effect.

The extensive number of measurements was carried out in order to examine a mechanism of this effect. They concerned the determination of main plasma parameters: electron temperature T_e and density n_e. Due to the presence of condensation in the area of interest (near a cooled electrode) the non-invasive methods of plasma diagnostics could only be used. For further application it was essential to have high spatial resolution of measurements. Owing to that the plasma was of low temperature and of high density the sensitivity of the methods applied was also important.

The obtained results served as the boundary conditions in a kinetic model of phenomena near a wall inserted in plasma in the presence of condensation at that wall. It was a set of Boltzmann kinetic equations with the Gross-Krook model collision term. The solution of it indicated that the condensation on a wall has a significant influence upon the quantity of ion flux [5].

2.1. Laser scattering diagnostics

Electromagnetic radiation, while passing through the plasma, undergoes scattering. This effect can be utilized for the plasma parameters examination. Taking into consideration the fact that only insignificant amount of light is scattered, it is necessary to apply a light source of the largest possible power. This condition is fulfilled by a pulse ruby laser; its additional advantage lying in the fact that its radiation is highly monochromatic, which makes it useful for laser plasma diagnostics methods utilizing light scattering effects.

One of the possible scattering regimes was considered, namely the scattering on free electrons [6]. For this case it is possible to determine the electron temperature T_e on the basis of the half-width of a scattering profile which can be obtained experimentally and is described by

$$\Delta\lambda = 4\pi\sqrt{2}\ln 2\,\frac{\lambda}{c}\sqrt{\frac{kT_e}{m}}\sin(\theta/2) \tag{3}$$

The experimental set-up is presented in Fig. 9.

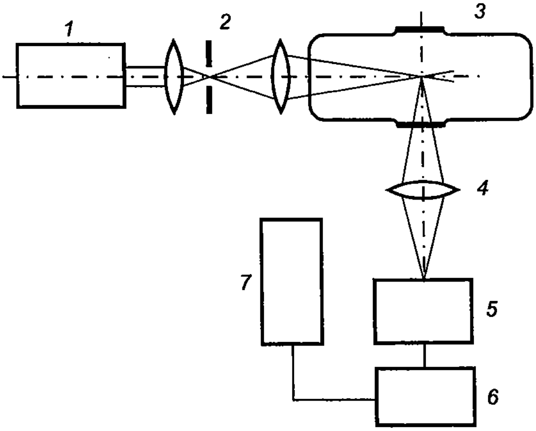

Fig. 9. Experimental set-up: *1* – ruby laser, *2* – optic set-up, *3* – plasma tube, *4* – viewing lens, *5* – double monochromator, *6* – photomultiplier, *7* – oscilloscope

The particular attention was paid to the elimination of the influence of destructively scattered light and the plasma self-lighting (stray light), which implied special requirements for the measurement set-up. The scattering profile obtained as the result of measurements allowed the determination of T in the vicinity of a cooled electrode. It was equal to 8700 K ± 36%.

2.2. Spectral investigations

The spectral method was used to confirm the results of the scattering one. The aim of the experiment was to evaluate the electron temperature T_e on the basis of obtained dependency between electron density n_e and T_e [7]. The electron density was determined using another experimental method.

We have decided to use the spectral method as it does not cause any perturbations in the plasma. The basic difficulties in examining such plasma lie in the fact that it is not within the local thermal equilibrium (LTE). In particular there is no determined temperature and thus the basic distribution laws do not apply to this plasma. It results in the necessity of determining the magnitudes which cannot be computed in a simple way, due to the lack of LTE. The determination of the excited atoms concentration on the respective energy levels was considered. For this purpose the reabsorption method with the application of a single mirror was used. The measurement set-up scheme is presented in Fig. 10. The subject of measurements was the plasma self-absorption.

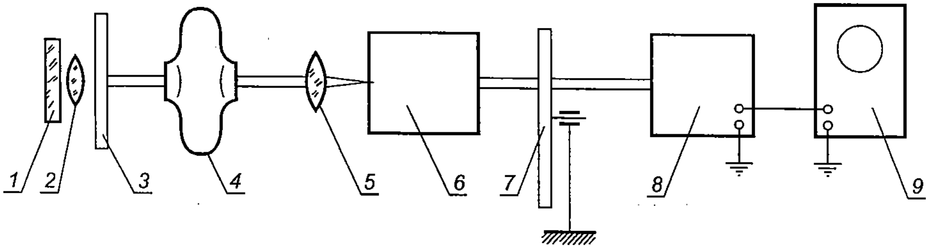

Fig. 10. The measurement set-up for plasma examination by absorption method: *1* – complete reflecting mirror, *2*, *5* – optical set-ups, *3* – curtain, *4* – plasma, *6* – monochromator, *7* – modulator, *8* – photomultiplier, *9* – oscilloscope

As a final result the dependency between n_e and T_e was obtained taking advantage of semi-empirical expressions of excitation rate $\langle \sigma_V \rangle$ and measuring the excited atom densities on the analyzed levels. Knowing the above dependency and electron density for this plasma, the electron temperature was calculated. The obtained results were compared with the results of the scattering method. A relatively good consistence of results was obtained.

2.3. The two-laser beam method

The two-laser beam method was elaborated in order to measure the electron density in a low-pressure plasma. The research was done in cooperation with the

Institute of Telecommunications and Acoustics, Wrocław University of Technology. The above-mentioned method is based on the measurement of the frequency shift that the laser undergoes due to the change in the refractive index of the resonator cavity caused by placing the examined plasma therein. The He-Ne laser has been used since a growth in laser wavelength increases the influence of electrons on the plasma refractive index. In order to detect the laser frequency changes caused by switching on the plasma, it is necessary to shift the high frequency generated by the laser into the radio range. This is possible when using the heterodyne method, depending on the beat of the examined beam with the beam of another laser working in the optical heterodyne system on the same wavelength. The introduction of periodic interruption of discharge in the plasma cell and of the homodyne detection method made it possible to eliminate the influence of neutral atoms and to measure the electron density with very high accuracy and sensitivity starting from 10^{16} m^{-3}. Furthermore, as a result of the Abel transformation, the radial electron density has been obtained [8].

The experimental set-up is shown in Fig. 11.

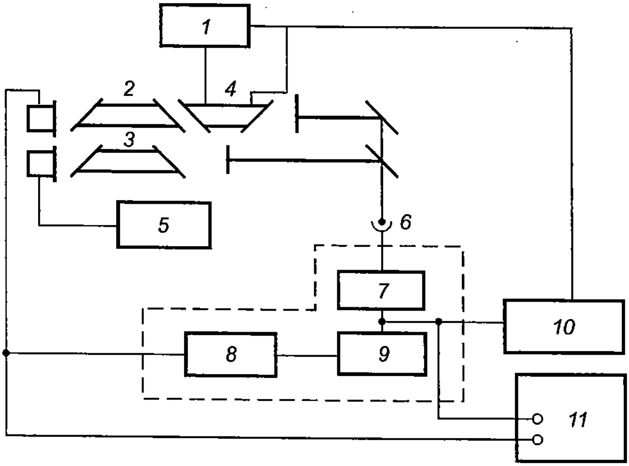

Fig. 11. Experimental set-up: *1* – supply and commutation set-up, *2, 3* – He-Ne 3.39 μm, *4* – plasma, *5* – voltage regulator, *6* – detector, *7+8+9* = feedback-loop, *10* – lock-in, *11* – oscilloscope

2.4. Plasma in a magnetic field

The second part of the research concerned plasma in an external magnetic field. The study of the basic properties of such plasmas is still of great scientific interest, mainly due to the controlled fission research. Steady-state plasma existing in devices of continuous operation, achieved by injecting a stream of plasma from an external source, is particularly convenient for the study of fluctuations, turbulence, currents driven across and along the magnetic field, etc.

Although the plasma under consideration here is cool (a few eV electron temperature) and weakly ionized, the mean free path is long and the plasma is only weakly coupled to the neutral background gas, so that research on these devices is relevant to the controlled fission research. It is very important that experimental installations are relatively simple and cheap in this case.

The problem of plasma injection into a magnetic field has not been described satisfactorily yet, especially that it is impossible to obtain a general solution because the final form of the problem depends on the specific experimental configuration as well. We were interested in the plasma injection into the so-called linear system. For the reasons mentioned above it was necessary to carry out the measurements to determine the basic plasma parameters for different conditions of injection. The aim of this research was to determine experimentally the dependence between electron temperature and density, plasma beam geometry and the intensity of externally imposed magnetic field in several points of the examined system. A series of measurements of an actual magnetic field in the entrance part of the system has been performed as well. The Langmuir probes were used for n_e, T_e measurements and Hall probe for magnetic field ones.

All measurements were made by B. Gorczyca in the Plasma Physics Laboratory, the Institute of Science and Technology, University of Manchester. The special attention was paid to the entrance part of the system where the magnetic field is curved. Fig. 12 shows the electron distribution along the diameter of plasma vessel for different intensities of an external magnetic field.

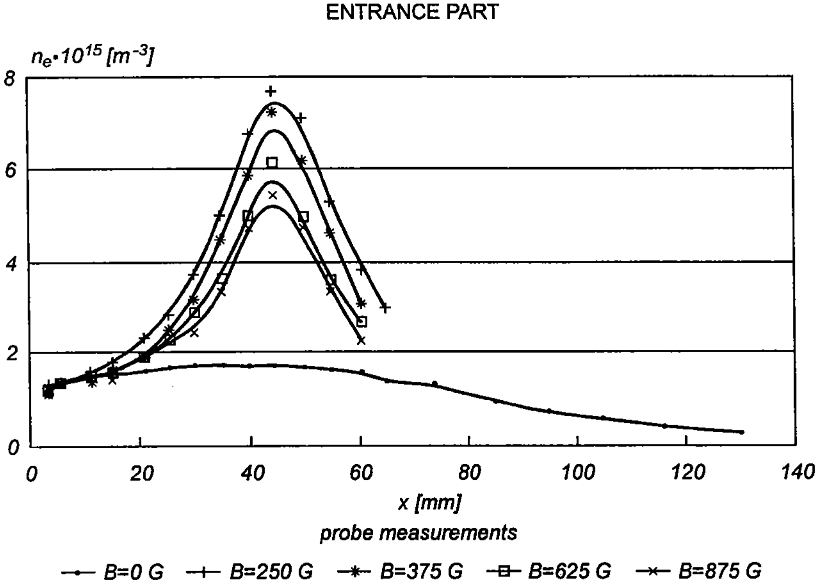

Fig. 12. Electron density distribution

The obtained results showed that the width of the beam in the entrance part depends strongly on the main magnetic field and that for higher values of B the influence of a transverse component of a field is significant [9]. This field was measured by means of a Hall probe. On the basis of the obtained results and the extensive literature review at first it has been concluded that any existing theoretical description of injection into magnetic field could not be applied to the linear system. Then, it has been proved that the polarization drift model is appropriate in this case and preliminary mathematical description has been formulated. Furthermore, some improvement of injection conditions has been obtained taking advantage of the experimental results.

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BADANIA PLAZMOWE W ZAKŁADZIE TERMODYNAMIKI

Streszczenie

W pracy omówiono wyniki ostatnio prowadzonych prac teoretycznych i doświadczalnych dotyczących plazmy nisko- i wysokotemperaturowej. W pracach teoretycznych związanych

z badaniami plazmy niskotemperaturowej bada się plazmę w stanie lokalnej równowagi termodynamicznej (LTR), jak i w stanie nierównowagi termicznej, w której temperatura elektronów jest różna od temperatury cząsteczek ciężkich ($T_e \neq T_h$). Innym rodzajem nierównowagi, nad którym aktualnie prowadzi się prace badawcze, jest nierównowaga jonizacyjna. Celem tych prac jest analiza zjawisk transportowych plazmy izo- i anizotropowej, o anizotropii wywołanej polami zewnętrznymi: elektrycznym i magnetycznym.

Część doświadczalna związana z plazmą niskotemperaturową dotyczy w szczególności efektu Kleina, a ogólnie metod pomiarowych w plazmie. Wykorzystuje się diagnostykę laserową i badania spektroskopowe. W badaniach nad plazmą fuzji prowadzi się prace badawcze związane z oddziaływaniem silnego pola magnetycznego na wtryskiwany strumień gazu w procesie kontrolowanej syntezy.

ИСПЫТАНИЯ ПЛАЗМЫ В КАФЕДРЕ ТЕРМОДИНАМИКИ

Краткое содержание

В работе представлены новейшие достижения Кафедры в области теоретических и экспериментальных испытаний низко- и высокотемпературной плазмы. В теоретических испытаниях низкотемпературной плазмы предметом анализа является плазма как в состоянии термодинамического равновесия, так и в состоянии термического неравновесия, при котором температура электронов не совпадает с температурой тяжелых частиц. Другим видом неравновесия является ионизационное неравновесие. Целью этих испытаний был анализ транспортных процессов изо- и анизотропной плазмы, в которой анизотропию генерируют магнитные и электрические поля. Экспериментальные работы посвященные низкотемпературной плазме в частности связаны с эффектом Кляйна, а в общих чертах с измерительной техникой. В этих испытаниях используются лазерные и спектральные техники.