*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, O-4.014 (2005)*

Heat Transfer in Dusty Plasma

I. Shakhova, A. Gavrikov, O. Vaulina, Yu. Khrustalyov, K. Statsenko, O. Petrov, V. Fortov

Institute for High Energy Densities RAS, Moscow, Russia

Dusty plasma arises every time dust (some disperse medium) is immersed into plasma. Particles of dust are macroscopic (size~10^{-4}-10^{-3} cm). These particles are usually called *macroparticles*. By this or that way a dusty particle gains electric charge which often amounts 10^3-10^4 elementary charges [1]. That is why dust in plasma is always the forth, charged, constituent part of plasma after electronic, ionic and neutral components. There is exchange of momentum, energy and charge between dusty component and other ones.

This work is devoted to investigation of thermal capacity of dusty component as individual subsystem. Thermal capacity (at constant pressure or volume (e.g. concentration)) in many respects determines the behaviour of thermal processes in a system.

Using of capacity definition $C = \delta Q / \delta T$ requires study of energy balance between external objects and all the components of plasma. The latter is irresolvable experimental task for today. Much easier is to use the relation [2]

$$c_V = \frac{\tilde{T}^2}{\delta \tilde{T}^2} \quad (2)$$

where $\delta \tilde{T}^2$ is squared fluctuation of temperature $\tilde{T}$, c_V – dimensionless thermal capacity at constant volume (e.g. concentration). The latter is related to molar capacity at constant volume by $C_V = c_V R$ where R is absolute gas constant. The value of c_V is determined not only by physical properties and state of system but by the amount of degrees of freedom which is of interest when one defines the temperature $\tilde{T}$. The temperature is the measure of mean kinetic energy of one particle. The most general form of it is:

$$\tilde{T} = \tfrac{1}{2} \sum_{\alpha=1}^{n_\gamma} m_\gamma \overline{\xi_{\alpha\gamma}^2}, \quad (3)$$

where γ is the number of motion type in which a separate particle can be involved.

As long as there is Maxwellian distribution of particles throughout velocity $\xi_{\alpha\gamma}$ in the system in question for mean square $\overline{\xi_{\alpha\gamma}^2}$ one can write

$$\overline{\xi_{\alpha\gamma}^2} = \int_{-\infty}^{+\infty} \xi_{\alpha\gamma}^2 f(\xi_{\alpha\gamma}) \cdot d\xi_{\alpha\gamma}, \quad (4)$$

$$f(\xi_{\alpha\gamma}) = \sqrt{\frac{m_d}{2\pi k\tilde{T}}} exp\left(-\frac{m_d \xi_{\alpha\gamma}^2}{2k\tilde{T}}\right), \quad (5)$$

and for the fluctuation:

$$\overline{\left(\xi_{\alpha\gamma}^2 - \overline{\xi_{\alpha\gamma}^2}\right)^2} = \int_{-\infty}^{+\infty} f(\xi_{\alpha\gamma})\left(\xi_{\alpha\gamma}^2 - \overline{\xi_{\alpha\gamma}^2}\right)^2 \cdot d\xi_{\alpha\gamma}. \quad (6)$$

After calculations we have

$$c_{V\alpha\gamma} = \frac{\left(\overline{\xi_{\alpha\gamma}^2}\right)^2}{\overline{\left(\xi_{\alpha\gamma}^2 - \overline{\xi_{\alpha\gamma}^2}\right)^2}} = \frac{1}{2} \quad (7)$$

for thermal capacity corresponding to temperature $\tilde{T} = \frac{1}{2} m_d \overline{\xi_{\alpha\gamma}^2}$. Thus for each degree of freedom under conditions of thermodynamic equilibrium there is capacity $c_{V\alpha\gamma} = \frac{1}{2}$, as widely known. So, we've just derived that (7) is property of a system in thermodynamic equilibrium. The experiment however shows that converse proposition is most likely incorrect. The macroparticles distributions regained empirically are close to Maxwellian one but they are not coincide precisely. Just now one could study only two horizontal transitional degrees of freedom of a macroparticle. That's why the investigation of thermal capacity corresponding to the temperature $\tilde{T} = \frac{1}{2} m_d \left(\overline{V_x^2} + \overline{V_y^2}\right)$ has been fulfilled. Empirically gained values of capacity c_V corresponding to this temperature are very close to unity (fig. 1) in wide range of values of parameter Γ^*, experimental curves for macroparticles distribution throughout velocity not coinciding completely with Maxwell ones.

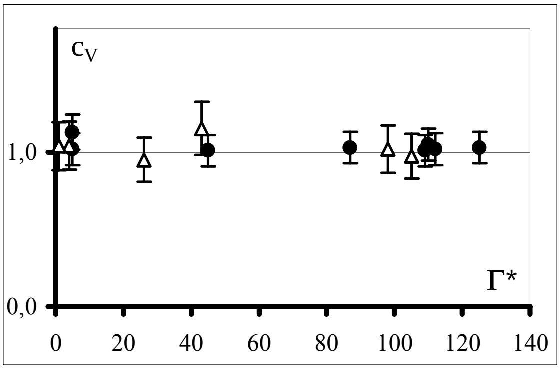

Fig. 1. The dependence $c_V(\Gamma^*)$.

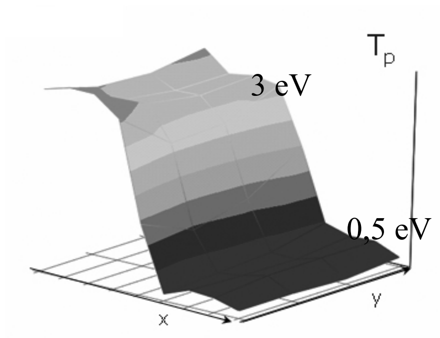

Fig. 2. Experimental temperature distribution.

Relation (2) allows one to determine capacity c_V for dusty component of plasma via observing it in some thermodynamic equilibrium state instead of studying its transfer from one state to another. This makes the task for an experimenter easier as much as it is easier to perform quasiequilibrium transfer between two very close states. Thus one can study experimentally the dependencies $c_V(T)$ and $c_V(\Gamma^*)$, where Γ^* is effective nonideality parameter depending monotonously on nonideality parameter [3,4]

$$\Gamma = u_p / \kappa_p \tag{8}$$

u_p – mean potential energy of a macroparticle in self-congruent field of dusty plasma and discharge, κ_p – its mean kinetic energy. Thus the dependence $c_V(\Gamma)$ gives information about the dependence $c_V(\Gamma)$.

Within the approach in use one can expect that the capacity measured c_V to be equal to 1, and this value must not depend on temperature $\tilde{T}$ as well as on parameter Γ as long as these concepts are not involved in final expression for $c_{V\alpha\gamma}$. However, one should bear in mind that with Γ^* changing the aggregative state of dusty component can change as well. This means that within different ranges of Γ^* values the character of macroparticle interaction is different too. All the calculations performed above are made in view of assumption that there are no collective processes in dusty plasma. This can be correct for gaseous or liquid states of dusty component. The situation might be more complex for crystal state. It is widely known that the crystallization in dusty component occurs at $\Gamma_c^* \approx 104$. For all values of $\Gamma^* > \Gamma_c^*$ one can expect changes in the capacity value due to the increased influence of collective processes.

In practice the measurement of c_V corresponding to the temperature $\tilde{T} = \frac{1}{2} m_d \left(\overline{V_x^2} + \overline{V_y^2} \right)$ were made in the following way. The capacity c_V was evaluated using formula (2). The temperature $\tilde{T}$ was derived from analysis of macroparticles distribution throughout velocity. The velocities for every particle were known for a number of close moments in time. These velocities were determined via macroparticles' position changes which were detected by a video camera. The distribution curves obtained empirically were approximated by Maxwell distribution via varying of the parameter T in the latter. The optimal value of this parameter was treated as temperature $\tilde{T}$. The temperature fluctuation

$$\delta\tilde{T}^2 = \frac{\sum_{i=1}^{n} (\kappa_i - \bar{\kappa})^2}{n}, \quad \kappa_i = \frac{1}{2} m_d V_i^2, \tag{9}$$

where all the values are determined for the one moment of time, n is the number of velocities in statistics.

In addition to measurement of thermal capacity our group managed to measure the thermal conductivity and thermal diffusivity. The stationary temperature distribution was observed (fig. 2). The measurement is based on Fourier law:

$$\vec{j} = -\chi \vec{\nabla} T \ , \tag{10}$$

on the formula for heat flux through a substance layer of thickness δx an of square S :

$$\vec{j} = \frac{\int \vec{V} m_d V^2 N F(V) dV}{S \Delta x} \approx \rho \left(\left\langle V_x^3 \right\rangle_+ - \left\langle V_x^3 \right\rangle_- \right), \tag{11}$$

F(V) – function of particles' distribution throughout velocity, ρ – dusty particles density, $\rho < V_x^3 >_{+,-}$ – heat flux carried in straight and opposite direction of Ox axis. Finally using experimental information about macroparticles velocities one obtains for thermal conductivity:

$$\chi = n \Delta x k_B \left(\left\langle V_x^3 \right\rangle_+ - \left\langle V_x^3 \right\rangle_- \right) \Big/ \left(\left\langle V_x^2 \right\rangle_+ - \left\langle V_x^2 \right\rangle_- \right), \tag{12}$$

and for thermal diffusivity

$$\vartheta = \chi \cdot \left(\frac{\rho \cdot c_V \cdot R}{m_d \cdot N_A} \right)^{-1} . \tag{13}$$

The empirical values are correspondingly

$\chi = (2,1 \pm 0,2) \cdot 10^{-14}\ Erg \cdot \left(s \cdot K \cdot cm \right)^{-1}$ and $\vartheta = \left(1,0 \pm 0,1\right) \cdot 10^{-2}\ \ cm^2 \cdot s^{-1}$.

Conclusion

In this work the thermal capacity along with thermal conductivity an diffusivity of dusty component of complex plasma were determined experimentally for the first time. The capacity is measured intermediately from the information about velocities of macroparticles, e.g. at the kinetic level. Along with the information about properties of dusty component the direct confirmation was obtained for the classical molecular-kinetic theory.

Acknowledgments

This work was partially supported by the RFFR (No. 04-02- 16362), CRDF (No. RU-P2-2593-MO-04), the Program of RAS Presidium and the RSSF.

References

1. Fortov V. E., Khrapak A. G., et all., UFN 5 (2004).
2. Landau L.D., Lifshitz E.M., Theoretical physics, vol. 5, Nauka, Moscow, 1976
3. Vaulina O.S., Vladimirov S.V., Petrov O.F., et al., Phys. Rev. Lett., 88, 245002 (2002).
4. Vaulina O.S. and Vladimirov S.V., Phys. Plasmas, 9, 835 (2002).