RADIANT HEAT TRANSFER IN ARGON PLASMA

S. S. Katsnel'son, V. G. Sevast'yanenko,
and R. I. Soloukhin

UDC 533.9:536.24:537.53

Integral radiation characteristics (over spectrum) are described for rapid calculation of heat transfer in systems containing argon with time-varying temperature and pressure fields.

A new integral method for calculation of radiant heat transfer in the real spectrum in the presence of a line structure was developed in [1-3]. Before solving the gas dynamic problem a complete integration is performed over frequency, and over angle, if the system has sufficient symmetry. Matrices of two types of functions are calculated, dependent only on the problem macroparameters, temperature, pressure, and geometric dimensions. Determination of the radiation field is reduced to selection and summation from the mass of characteristics. The time required for calculation of radiant heat transfer is small in comparison to the machine time required for solution of the gas dynamic problem, the reverse of the situation in traditional calculations. The method permits use of a gas dynamic grid, the steps in which are dependent solely on temperature, pressure, and velocity gradients, and does not require

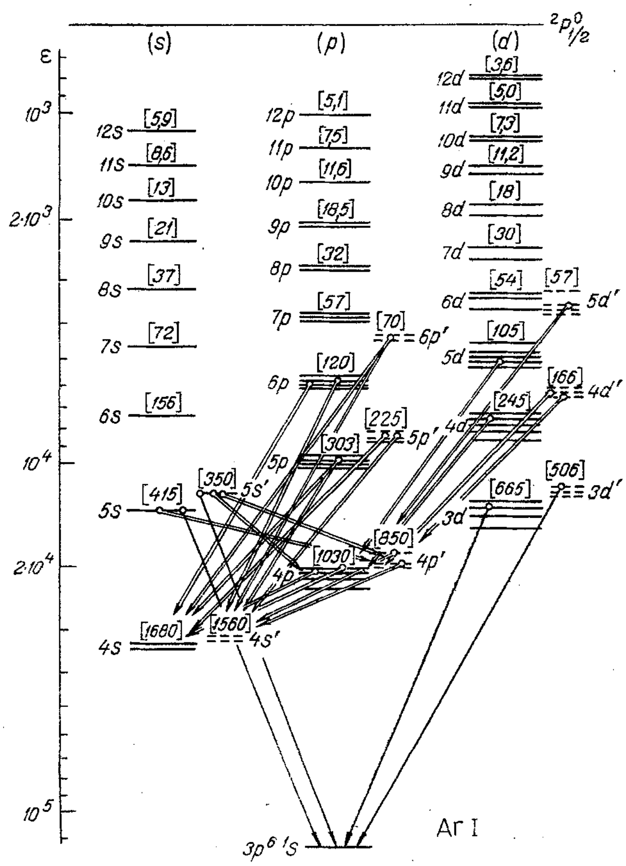

Fig. 1. Energy levels, ionizing field intensities (kV/cm), and transitions considered for argon atom, ε, cm^{-1}.

Theoretical and Applied Physics Institute, Siberian Branch, Academy of Sciences of the USSR, Novosibirsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 46, No. 2, pp. 299-303, February, 1984. Original article submitted July 5, 1982.

 0022-0841/84/4602-0224$08.50

introduction of special grids with step size dependent on optical density. It is quite simple and accessible to thermophysicists and gas dynamicists with no special training in atomic spectroscopy. The integral characteristics have the form of a set of smooth functions, easily introduced into computer memory.

The effective population method [3-5], based on a large volume of experimental material, produced spectral radiation characteristic values satisfactorily agreeing with measured values. The calculations consider the effects of a smooth transition of the line spectrum into a continuous one.

The use of a table of partial characteristics for calculation of radiant heat transfer in a hydrogen plasma was described in [6]. All the expressions and notation as well as Figs. 1, 3, 4 of [6] correspond fully to the argon partial characteristic tables to be described below. The radiant flux and flux divergence fields can be calculated for systems of any geometric form with arbitrary pressure and temperature distributions.

The argon spectrum was first studied in [7, 8], then in greater detail in [9]. In the present study the argon spectral and integral characteristics were calculated by the effective population method. Argon plasma composition, calculated with consideration of interaction of plasma particles, has been presented in [4, 10]. Figures 1 and 2 show diagrams of the argon atom ArI and argon ion ArII energy levels. The ionizing field intensities are shown in square brackets next to the corresponding levels. Multiplets considered (with the exception of transitions from f-configurations) are indicated by arrows. Probabilities of these transitions were taken from [11]. Photoionization from configurations 3p, 4a, and 4p of ArI was considered individually. Photoionization sections were taken from [12-16]. Photoionization from the remaining levels was determined by integral expressions from [3, 5]. The factors $\xi(\nu)$ were taken from [17, 18].

In calculating bound–free transitions from the ground and excited states both optical shift and the reduction in population of those levels from which photoionization produces a contribution at a given frequency were considered. The spectral line contours were approximated by a Foigt convolution. The following broadening mechanisms were considered: Stark effect, resonance, van der Waals, and Doppler. The data for calculation of Stark half-widths and Stark shift were taken from [19].

Figure 3 shows the partial intensity for bilinear splines. The solid curves correspond to splines preserving $\int T d\eta$ (data shown on left of Fig. 3). It is evident that as for other spectra (see [3]), the partial intensity curves are grouped together basically as a function of the source temperature T_ξ and practically coincide for splines which preserve $\int T d\eta$. As follows from Fig. 3, the effective optical density of the absorption path is conservative and good accuracy in radiation field calculation by the partial characteristic method can be achieved even with use of lower order splines (in particular, linear ones).

The error in calculating integral characteristics from the known absorption coefficient comprises 1%. The major inaccuracy is introduced by the absorption coefficient, which in various regions can be calculated only with an accuracy of 5-15%.

The proposed partial characteristic tables are intended for calculation of radiant intensities, flux fields, and flux divergences in systems with characteristic dimensions up to 1 m, containing hot argon at pressures from 0.1 to 30 bar and temperatures to 20,000°K.

The tables are entered with five input parameters (T_ξ, P_ξ, T_X, P_X, x). The source temperature T_ξ ranges from 6000 to 20,000°K in steps ΔT_ξ = 2000°K. The contribution to heat transfer from segments with temperature T_ξ < 6000°K is small, and may be taken equal to zero. The temperature of the calculated point (or drain) T_X is given from 2000°K to 20,000°K in steps ΔT_X = 2000°K. For points of a volume in which the temperature T_X < 2000°K one can use the value of 2000°K with insignificant error.

For convenience in interpolation the pressure and geometric dimension scales are presented logarithmically. The log of the pressure (in bar) ranges from –1 to 1.5, which allows calculation at pressures from 0.1 to ≈30 bar. The log of x (cm) ranges from –2 to +2, corresponding to dimensions from 0.1 mm to 1 m.

The table entries are in mantissa-characteristic form. Thus an entry of 81 + 01 corresponds to a value of $0.81 \cdot 10^{-1}$.

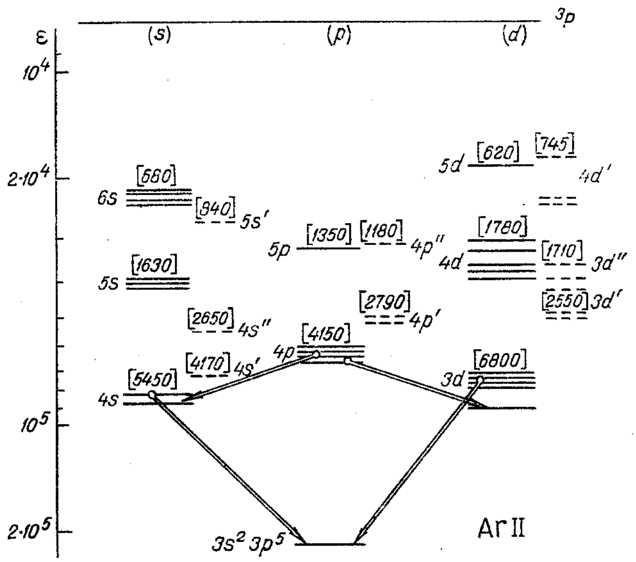

Fig. 2. Energy levels, ionizing field intensities (kV/cm), and transitions considered for argon ion, ε, cm^{-1}.

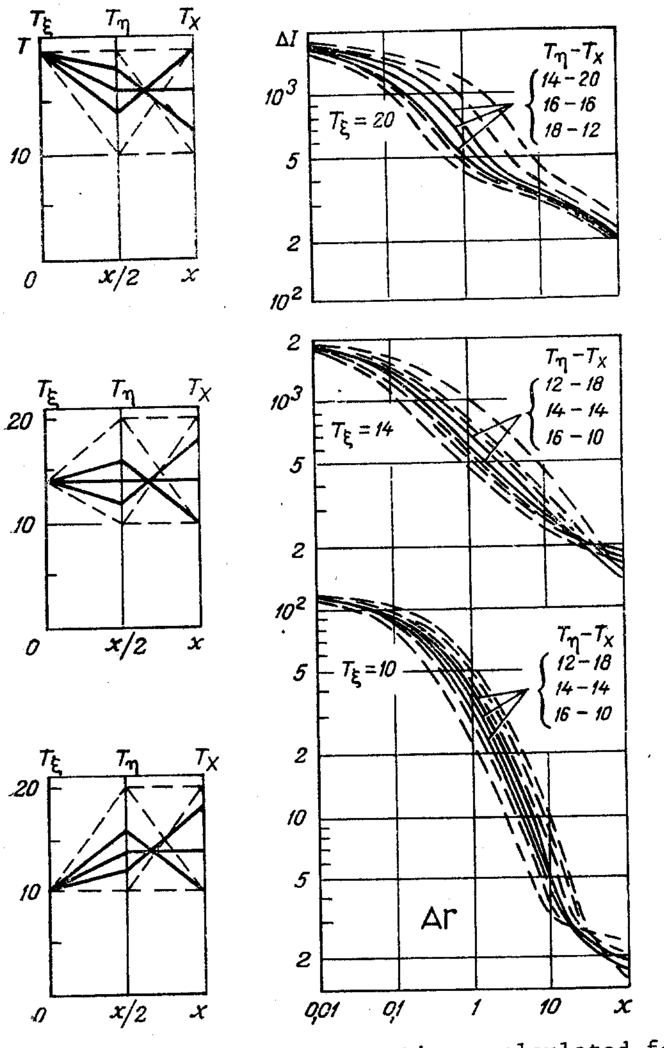

Fig. 3. Partial intensity conservation, calculated for bi-linear splines ($T \cdot 10^{-3}$ deg K), ΔI, $W/cm^3 \cdot St$; x, cm.

The dimensions of the partial characteristics and results of their integration are as follows: ΔI, $W \cdot cm^{-3} \cdot St^{-1}$; ΔSim, $W \cdot cm^{-4} \cdot St^{-1}$; I, $W \cdot cm^{-2} \cdot St^{-1}$; ∇I, $W \cdot cm^{-3} \cdot St^{-1}$; S, $W \cdot cm^{-2}$; ∇S, $W \cdot cm^{-3}$.

Using these tables, radiation fields can be calculated from known temperature and pressure fields with the expressions presented in [1-3] and [6].

The tables described above can be obtained from the Institute of Theoretical and Applied Mechanics, Siberian Branch, Academy of Sciences of the USSR (630090, Novosibirsk-90, Institutskaya 4/1). The tables are available in analog form with analog–digital conversion, on punched cards, or may be recorded on the user's magnetic tape. The last method is preferred.

NOTATION

T, absolute temperature; P, pressure; x, X, ξ, η, geometric coordinates.

LITERATURE CITED

1. V. G. Sevast'yanenko, "Radiant transfer in the real spectrum. Integration over frequency," Inzh.-Fiz. Zh., 36, No. 2, 218-230 (1979).
2. V. G. Sevast'yanenko, "Radiant transfer in the real spectrum. Integration over angles," Inzh.-Fiz. Zh., 38, No. 2, 278-285 (1980).
3. V. G. Sevast'yanenko, "Radiant heat transfer in the real spectrum," Author's Abstract of Doctoral Dissertation, Novosibirsk (1980).
4. G. A. Koval'skaya and V. G. Sevast'yanenko, "Equilibrium properties of low temperature plasma," in: Low Temperature Plasma Properties and Diagnostic Methods [in Russian], Nauka, Novosibirsk (1977), pp. 11-37.
5. V. G. Sevast'yanenko, Effect of Particle Interaction in Low Temperature Plasma on Composition and Optical Properties. Preprints Nos. 30, 32, Inst. Teor. Prikl. Mekh., Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1980).
6. G. A. Koval'skaya, V. G. Sevast'yanenko, and R. I. Soloukhin, "Radiant heat transfer in hydrogen plasma," Inzh.-Fiz. Zh., 45, No. 6, 977-983 (1983).
7. V. G. Sevast'yanenko and I. T. Yakubov, "Radiant cooling of a gas heated by an intense shock wave," Opt. Spektrosk., 16, No. 1, 3-10 (1964).
8. I. T. Yakubov, "Energy radiated by argon plasma on spectral lines," Opt. Spektrosk., 19, No. 4, 497-500 (1965).
9. S. P. Vagin, S. S. Katsnel'son, and V. I. Yakovlev, "Calculation of radiation characteristics of argon plasma," in: Methods for Study of Radiant Properties of Media [in Russian], Inst. Teor. Prikl. Mekh., Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1977), pp. 30-180.
10. G. A. Koval'skaya and V. G. Sevast'yanenko, "Plasma composition and thermodynamic properties," in: Physical Kinetics [in Russian], Inst. Teor. Prikl. Mekh., Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1974), pp. 1-78.
11. W. L. Wiese, M. W. Smith, and B. M. Glennon, Atomic Transition Probabilities, NBS USA (1966).
12. A. N. Lagar'kov and I. T. Yakubov, "Effect of radiation on gas state ahead of a shock wave front," Opt. Spektrosk., 14, No. 2, 199-207 (1963).
13. A. A. Kon'kov and S. G. Kulagin, "Study of argon plasma at temperatures of 12,000-16,000°K, Teplofiz. Vys. Temp., 12, No. 3, 497-501 (1974).
14. J. A. R. Samson, "The measurement of photoionization cross section of the atomic gases," Adv. Atom. Mol. Phys., 2, 177-261 (1966).
15. É. I. Asinovskii and V. M. Batenin, "Experimental study of the continuous spectrum of argon plasma," Teplofiz. Vys. Temp., 3, No. 4, 530-575 (1965).
16. G. A. Kobzev and V. M. Sergeev, "Approximate method for calculation of photoionization cross sections of atoms and ions," Opt. Spektrosk., 33, No. 6, 1019-1027 (1972).
17. L. M. Biberman and G. É. Norman, "Continuous spectra of atomic gases and plasma," Usp. Fiz. Nauk, 91, No. 2, 193-246 (1967).
18. D. Schlueter, "Die Emissionskontinua thermischer Edelgasplasmen," Zs. Phys., 210, No. 1, 80-91 (1968).
19. G. Grim, Spectral Line Broadening in Plasma [Russian translation], Mir. Moscow (1978).