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Mgr. Nadezda Bogatyreva

Radiation Transfer of Energy in Arc Plasma

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
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Mgr. Nadezda Bogatyreva

RADIATION TRANSFER OF ENERGY IN ARC PLASMA

RADIAČNÍ PŘENOS ENERGIE V OBLOUKOVÉM PLAZMATU

Zkrácená verze Ph.D. Thesis

Obor:	Fyzikální elektronika a nanotechnologie
Vedoucí práce:	doc. RNDr. Milada Bartlová, Ph.D.
Oponenti:	prof. RNDr. Vratislav Kapička, DrSc.
	Ing. M.S.M.E. Jiří Jeništa, CSc.
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1. INTRODUCTION

1.1. STATE OF ART

The transfer process of radiation energy plays an important role in many devices of plasma treatment. Plasma electric arcs are used in industry, for instance in plasma metallurgy, plasma cutting, formation and modification of surface structure, waste treatment, etc. Fluxes of thermal plasma are produced in plasma generators. The most spread ones are the generators with the electric arc stabilized by gas flux such as argon, nitrogen or the mixtures of these gases with hydrogen and helium.

Another important field of application of thermal plasma is electric arcs in high power circuit breakers. The basic mechanism is used for all types of the circuit breakers, i.e. the extinguishing of a switching arc at the natural current zero by gas convection. From the point of view of extinguishing properties the best circuit breaker is the SF_6 self-blast one. The switching arc burns inside the narrow nozzle made of synthetic material PTFE. Due to high emission of radiation from the arc, the synthetic material is ablated and causes an exceeded pressure within the nozzle. Thus, the gas flux is transferred to the circuit breaker. In this case the plasma is a mixture of products of dissociation and ionization of SF_6, PTFE and metal admixtures of electrodes.

Gathering the information about physical processes occurring in the electric arc by means of ordinary measuring is very difficult due to extreme experimental conditions, i.e. high temperature, pressure and velocity of gas flux movement. In that case, the mathematical modeling plays an important role. Nevertheless, the one faces very complicated mathematical model of plasma due to nonlinear equations describing the radiation field and the high influence on frequency and properties of radiation medium of input parameters. In addition, there are difficulties due to the complicated structure of plasma absorption spectrum that might consist of thousands of spectral lines. In turn, the absorptivity could differ by several orders of magnitude within similar frequency ranges. In that case, the one should integrate the radiation from all elements simultaneously by all particular directions and all solid angles. Thus, the direct frequency integration of the spectral characteristics of radiation is impossible in practice, even by means of modern computers due to vast time consumption. Thereupon, in order to calculate the radiation transfer in the arc plasma, several methods of approximation were introduced.

1.2. OBJECTIVES OF THE DISSERTATION

The thesis is of theoretical nature. The aims of dissertation are:

- to study the problems of radiation transfer in thermal plasma;
- to focus on the approximate method of spherical harmonic functions (P_N-approximation);

- to prepare a suitable computational code;
- to find radiation characteristics (radiation intensity, radiation energy density, radiation flux, divergence of radiation flux) for selected types of plasma;
- to compare obtained results with data obtained by means of the method of partial characteristics and the method of net emission coefficients, calculated previously at FEEC BUT.

2. RADIATION TRANSFER IN THERMAL PLASMA

2.1. ENERGY BALANCE OF ARC PLASMA

Electric discharge plasmas transmit relatively great deal of power. The ratios while transmission are described by the energy balance of the plasma. In the theory of the energy balance of the plasma only the element of the plasma volume is taken into consideration and heat convection is neglected.

The energy balance of the arc plasma in stationary state can be described by Ehlenbaas – Heller equation [1]

$$\sigma_E E^2 = -\mathrm{div}(\lambda \,\mathrm{grad}\, T) + \mathrm{div}\, \vec{W}_R , \tag{1}$$

where $\sigma_E E^2$ denotes the input electric power (σ_E is the electric conductivity, E is the electric field); $\lambda \cdot \mathrm{grad} T$ denotes the energy flux due to heat conduction (λ is the heat conductivity, T is the plasma temperature); $\mathrm{div}\vec{W}_R$ denotes the losses of energy by radiation ($\vec{W}_R$ is the radiation flux).

Therefore, for modeling of arc plasma including radiation it is necessary to determine the radiation flux and its divergence.

2.2. RADIATION TRANSPORT

The main quantity describing the radiation is the radiation intensity I. The radiation energy that passes through a cross section dS within the solid angle element dΩ in the direction θ with respect to the surface normal $\vec{n}$, during a time interval dt at frequencies between ν and ν+dν, contains an amount of energy given by

$$\mathrm{d}E_\nu(\vec{r},\theta,\varphi) = I_\nu(\vec{r},\theta,\varphi)\ \mathrm{d}\nu\ \mathrm{d}S\ \cos\theta\ \mathrm{d}\Omega\ \mathrm{d}t . \tag{2}$$

The quantity $I_\nu(\vec{r},\theta,\varphi) \equiv I_\nu(\vec{r},\vec{\Omega})$, which refers to unit surface, unit time, and unit frequency, is called the spectral radiation intensity. Here, $\vec{r}$ is a position vector fixing the location of a point in space and $\vec{\Omega}$ is a unit direction vector. [2]

The total intensity is obtained by integrating over all frequencies:

$$I(\vec{r},\vec{\Omega}) = \int_0^\infty I_\nu(\vec{r},\vec{\Omega})\mathrm{d}\nu \,. \tag{3}$$

Spectral density of radiation energy is given by

$$U_\nu(\vec{r},\nu) = \frac{1}{c}\int_{4\pi} I_\nu(\vec{r},\vec{\Omega},\nu)\mathrm{d}\Omega \,, \tag{4}$$

where c is velocity of light.

The spectral radiation flux is the radiation energy in frequency interval $\mathrm{d}\nu$ passing per unit time and unit area normal to the rays

$$\vec{W}_{R\nu}(\vec{r},\nu) = \int_{4\pi} I_\nu(\vec{r},\vec{\Omega},\nu)\vec{\Omega}\mathrm{d}\Omega \,. \tag{5}$$

Like to (3), we can define the total density of radiation and total radiation flux by integration over frequency:

$$U(\vec{r}) = \int_0^\infty U(\vec{r},\nu)\mathrm{d}\nu \,, \tag{6}$$

$$\vec{W}_R(\vec{r}) = \int_0^\infty \vec{W}_{R\nu}(\vec{r},\nu)\mathrm{d}\nu \,. \tag{7}$$

A light beam traveling through a participating gas layer of thickness ds loses energy by absorption and by scattering away from the direction of travel. The attenuation of radiation is proportional to the magnitude of the incident energy (intensity I_ν) and to the length of the path

$$\mathrm{d}I_\nu = -\kappa_\nu I_\nu \mathrm{d}s \,. \tag{8}$$

The proportionality constant κ_ν is known as extinction coefficient

$$\kappa_\nu = \kappa^a + \kappa^s \,, \tag{9}$$

where κ^a, κ^s are absorption and scattering coefficients, resp. [2] The negative sign has been introduced since the intensity decreases.

Because scattering of photons by molecules and atoms is always negligible for heat transfer applications we put $\kappa_\nu = \kappa^a$.

At the same time the light beam gains energy by emission, the emitted intensity is proportional to the path length

$$\left(\mathrm{d}I_\nu\right)_{em} = \varepsilon_\nu \mathrm{d}s \,, \tag{10}$$

where ε_ν is the emission coefficient.

For a parallel beam of radiation intensity I_ν, the increase in intensity across an element of thickness ds is given by the difference between emission and absorption due to the element:

$$\mathrm{d}I_\nu = \varepsilon_\nu \mathrm{d}s - I_\nu \kappa_\nu \mathrm{d}s\,. \tag{11}$$

In local thermodynamic equilibrium

$$\varepsilon_\nu = B(\nu)\kappa_\nu\,, \tag{12}$$

where $B(\nu)$ is Planck's spectral radiation intensity for equilibrium radiation.

The complete stationary equation of radiation transfer for an absorbing and emitting medium is

$$\vec{\Omega}\cdot \mathrm{grad}\ I_\nu = \kappa_\nu (B(\nu) - I_\nu)\,. \tag{13}$$

3. ABSORPTION PROPERTIES OF PLASMA

When a photon interacts with a gas molecule, atom, or ion, it may be absorbed raising the particle's energy level. Conversely, a gas particle may spontaneously lower its energy level by the emission of an appropriate photon. There are three different types of radiative transitions that lead to a change of gas particle energy level by emission or absorption of a photon: [2]

- transition between non-dissociated („bound“) atomic or molecular states, called *bound-bound transitions (bb)*;
- transitions from a „bound“ state to a „free“ (dissociated) one (absorption) or from „free“ to „bound“ (emission), called *bound-free transitions (bf)*;
- transitions between two different „free“ states, called *free-free transitions (ff)*.

The total absorption coefficient is given as linear sum of all three processes mentioned above [2]

$$\kappa(\nu, T, p) = \kappa^{ff} + \kappa^{bf} + \kappa^{bb}\,. \tag{14}$$

Calculation of absorption coefficient represents a formidable task when experimental data are lacking, since the radial wave functions of all free and bound electronic states must be known. However, simplifications can be made by using various semi-empirical methods.

Radiation in arc plasma depends, besides others physical quantities, on concentrations of all chemical species occurring in the plasma. Equilibrium compositions of different types of plasma can be computed using *Tmdgas* computer code which is part of the database system *TheCoufal*, available at http://www.feec.vutbr.cz/~coufal [3], [4]. Input data for the composition calculation are specific enthalpy and standard thermodynamic functions of all accounted species.

At our Faculty, a computer code was developed for calculation of absorption coefficients in thermal plasmas, and a database of input parameters for many types of plasma was created. An example of absorption coefficient of air at the pressure of

0,1 MPa (1atm) and temperatures 1 000 and 10 000 K is shown in Fig. 1. This spectrum is a complex of discrete and continuous spectra.

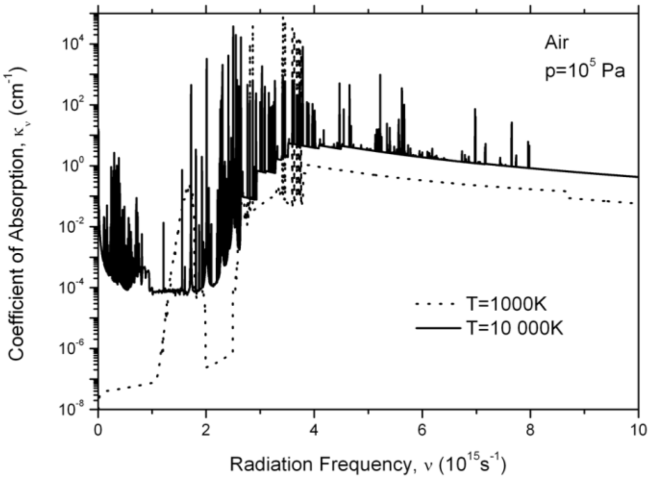


Fig. 1. Absorption coefficient of air thermal plasma as a function of frequency (calculated using computer code [5]).

4. APPROXIMATE METHOD OF SPHERICAL HARMONIC FUNCTIONS

4.1. GENERAL P_N-APPROXIMATION

The equation of transfer is obviously very complicated; the spectral intensity, which is the dependent variable in this equation, depends in general upon independent variables $(\vec{r}, \nu, \vec{\Omega})$. One must approximate the equation of transfer, either analytically or numerically, in order to obtain a solution. Due to the non-linearity of equations describing the radiation field and strong dependence of input parameters on the radiation frequency, various approximate methods are used. One of them is the method of spherical harmonics - P_N-approximation.

This method enables to obtain an approximate solution of arbitrary high accuracy by transforming the equation of transfer into a set of simultaneous partial differential equations. The approach was first proposed by Jeans [6] for radiation transfer in stars, many works was done by Davison [7] for transfer in the closely related neutron transport theory.

The spectral radiation intensity can be expressed in terms of Fourier series as

$$I_\nu(\vec{r}, \vec{\Omega}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} I_l^m(\vec{r}) Y_l^m(\vec{\Omega}), \qquad (15)$$

where $I_l^m(\vec{r})$ are position dependent coefficients and $Y_l^m(\vec{\Omega})$ are spherical harmonics:

$$Y_l^m(\vec{\Omega}) = (-1)^{(m+|m|)/2}\left[\frac{(l-|m|)!}{(l+|m|)!}\right]^{1/2} \exp^{im\psi} P_l^{|m|}(\cos\theta). \tag{16}$$

Here, θ and ψ are the polar and azimuthal angles describing the direction unit vector $\vec{\Omega}$, respectively, and P_l^m are associated Legendre polynomials.

We substitute the expression of intensity (15) into the equation of radiation transfer (13), equation is then multiplied by Y_k^n and integrated over all directions. Using the orthogonality properties of spherical harmonics, infinite system of coupled partial differential equations in the unknown position dependent functions $I_l^m(\vec{r})$ is obtained. For infinite number of equations the above representation is an exact method for the determination of radiation intensity. An approximation is made by truncating the series in (15) after N terms. In this way, the single unknown function I, which is a function of space and direction, is replaced by $(N + 1)^2$ unknown I_l^m that are functions of space only. The complexity of the system of equations for $I_l^m(\vec{r})$ depends on the geometry of the plasma system considered. The simplest system is the one-dimensional plane-parallel medium. In this case, the intensity I does not depend on azimuthal angle ψ, i.e. $I_l^m = 0$ for $m \neq 0$.

The great advantage of the method of spherical harmonics is the conversion of the equation of transfer to relatively simple partial differential equations. However, the low-order approximations are usually only accurate in optically thick media and for higher-order approximations mathematical complexity increases rapidly. It is known from neutron transport theory that approximations of odd orders are more accurate than even ones. Due to its simplicity, mainly the lowest order P_N solution corresponding to $N = 1$ (P_1-approximation) is usually used (so called diffusion approximation). The diffusion approximation describes in good accuracy the radiation field in many problems of radiation hydrodynamics.

4.2. P_1-APPROXIMATION (DIFFUSION APPROXIMATION)

In P_1-approximation we suppose that the angular dependence of the specific intensity can be represented by the first two terms in a spherical harmonic expansion

$$I_\nu(\vec{r},\nu,\vec{\Omega}) = \varphi_1(\vec{r},\nu) + 3\vec{\varphi}_2(\vec{r},\nu)\cdot\vec{\Omega}, \tag{17}$$

where φ_1 and $\vec{\varphi}_2$ correspond to the density of the radiation field multiplied by velocity of light c, and to the radiation flux. [8]

The spectral density of the radiation field is

$$U_\nu(\vec{r},\nu) = \frac{1}{c}\int_0^{4\pi} I_\nu(\vec{r},\nu,\vec{\Omega})\,\mathrm{d}\Omega = \frac{4\pi}{c}\varphi_1(\vec{r},\nu) \tag{18}$$

Likewise, for radiation flux we obtain

$$\vec{W}_\nu(\vec{r},\nu) = \int_0^{4\pi} I_\nu(\vec{r},\nu,\vec{\Omega})\vec{\Omega}\,\mathrm{d}\Omega = 4\pi\,\vec{\varphi}_2(\vec{r},\nu)\,. \tag{19}$$

Integrating the equation of radiation transfer (13) over all solid angles we obtain the diffusion equation for the spectral density of radiation field

$$-\mathrm{div}\left[\frac{c}{3\kappa_\nu}\mathrm{grad}U_\nu\left(\vec{r},\nu\right)\right] + \kappa_\nu c U_\nu\left(\vec{r},\nu\right) = \kappa_\nu 4\pi\, B\left(\nu\right), \tag{20}$$

and for the radiation flux

$$\vec{W}_\nu(\vec{r},\nu) = -\frac{c}{3\kappa_\nu}\mathrm{grad}U_\nu(\vec{r},\nu) \tag{21}$$

The diffusion approximation is valid under assumption that the spectral radiation intensity is almost isotropic.

5. MULTIGROUP METHOD

One of the methods for handling the frequency variable in the equation of transfer is the multigroup method [9], which leads to its discretization. One assigns a given photon to one of G frequency groups, and all photons within a given group are treated the same from the point of view absorption properties of the medium, the absorption coefficient for given frequency group k is supposed to be constant with certain average value

$$\kappa_\nu\left(\vec{r},\nu,T\right) = \kappa_k\left(\vec{r},T\right), \quad \nu_k \le \nu \le \nu_{k+1}\,, \quad k = 1,....,G\,. \tag{22}$$

The values of total intensity, total density of radiation, and total radiation flux are then given by

$$I\left(\vec{r},\vec{\Omega}\right) = \sum_{k=1}^{G} I_k\left(\vec{r},\vec{\Omega}\right), \qquad I_k\left(\vec{r},\vec{\Omega}\right) = \int_{\nu_k}^{\nu_{k+1}} I_\nu\left(\vec{r},\nu,\vec{\Omega}\right)\mathrm{d}\nu \tag{23}$$

$$U\left(\vec{r}\right) = \frac{1}{c}\int_0^\infty \mathrm{d}\nu \int_{4\pi} I_\nu\left(\vec{r},\nu,\vec{\Omega}\right)\mathrm{d}\Omega = \frac{1}{c}\sum_{k=1}^{G}\int_{4\pi} I_k\left(\vec{r}.\vec{\Omega}\right)\mathrm{d}\Omega \tag{24}$$

$$\vec{W}_R\left(\vec{r}\right) = \int_0^\infty \mathrm{d}\nu \int_{4\pi} \vec{\Omega}\, I_\nu\left(\vec{r},\nu,\vec{\Omega}\right)\mathrm{d}\Omega = \sum_{k=1}^{G}\int_{4\pi} \vec{\Omega} I_k\left(\vec{r},\vec{\Omega}\right)\mathrm{d}\Omega\,. \tag{25}$$

The equation of transfer for the given frequency group can be treated as equation for grey medium:

$$\vec{\Omega}\cdot\mathrm{grad}\, I_k(\vec{r},\vec{\Omega}) = \overline{\kappa}_k\left(\int_{\nu_{k-1}}^{\nu_k} B(\nu)\mathrm{d}\nu - I_k(\vec{r},\vec{\Omega})\right), \quad 1 \le k \le G, \tag{26}$$

$\overline{\kappa}_k$ is the mean absorption coefficient defined as

$$\overline{\kappa}_k = \frac{\int\limits_{\nu_{k-1}}^{\nu_k} \kappa_\nu(\nu)\left[B(\nu) - I_\nu\left(\vec{r},\nu,\vec{\Omega}\right)\right]\mathrm{d}\nu}{\int\limits_{\nu_{k-1}}^{\nu_k}\left[B(\nu) - I_\nu\left(\vec{r},\nu,\vec{\Omega}\right)\right]\mathrm{d}\nu} . \tag{27}$$

For P_1-approximation the multigroup diffusion equation (25) has the form

$$-\mathrm{div}\left[\frac{c}{3\overline{\kappa}_k}\mathrm{grad}U_k\left(\vec{r}\right)\right] + \overline{\kappa}_k c U_k\left(\vec{r}\right) = \overline{\kappa}_k 4\pi \int\limits_{\nu_{k-1}}^{\nu_k} B(\nu)\, d\nu , \tag{28}$$

6. MEAN ABSORPTION COEFFICIENTS

For the multigroup method to be useful, one must be able to compute or estimate the mean values of absorption coefficients (27). An exact calculation of these group constants involves knowledge of the spectral intensity $I\left(\vec{r},\nu,\vec{\Omega}\right)$ which is unknown. The underlying assumption in the multigroup method is that the group constants are relatively insensitive to the weighting functions $I\left(\vec{r},\nu,\vec{\Omega}\right)$ used in computing the averages over frequency. The accuracy of the method depends also on the interval splitting. As the group width approaches zero the group constant become independent upon the estimate made for $I\left(\vec{r},\nu,\vec{\Omega}\right)$.

Absorption coefficients are generally complex and widely varying functions of frequency (as can be seen at Fig. 1), and the use of different weighting functions $I\left(\vec{r},\nu,\vec{\Omega}\right)$ can lead to quite different results. Generally, $\overline{\kappa}_k$ is taken as either Rosseland or Planck mean.

The Rosseland mean, also called mean free path of radiation is appropriate when the system approaches equilibrium (almost all radiation is reabsorbed). It has the form

$$\overline{\kappa_R^{-1}} = \frac{\int\limits_{\nu_{k-1}}^{\nu_k} \kappa_\nu^{-1}\frac{\mathrm{d}B(\nu,T)}{\mathrm{d}T}\mathrm{d}\nu}{\int\limits_{\nu_{k-1}}^{\nu_k}\frac{\mathrm{d}B(\nu,T)}{\mathrm{d}T}\mathrm{d}\nu} . \tag{29}$$

The Planck mean is appropriate in the case of optically thin, emission dominated system. It can be expressed as

$$\overline{\kappa}_P = \frac{\int\limits_{\nu_{k-1}}^{\nu_k}\kappa_\nu B(\nu,T)\mathrm{d}\nu}{\int\limits_{\nu_{k-1}}^{\nu_k} B(\nu,T)\mathrm{d}\nu} . \tag{30}$$

7. APPLICATIONS

7.1. AIR PLASMA

In calculation of plasma composition the dry air was assumed at the pressure of US standard atmosphere from sea level [10] consisting of N_2, O_2, Ar, and CO_2. An equilibrium composition of the air plasma was computed using *Tmdgas* code [3], [4]. Atoms and up to the triple ions of N, O, Ar, C elements, respectively, and diatomic molecules O_2, N_2, N_2^+, NO, NO^+ were assumed.

Calculated total spectral coefficients of absorption (continuum, lines and molecular bands) at various plasma temperatures are shown in Fig. 1. High complexity of radiation absorption coefficients (with respect to frequency and temperature) can be seen.

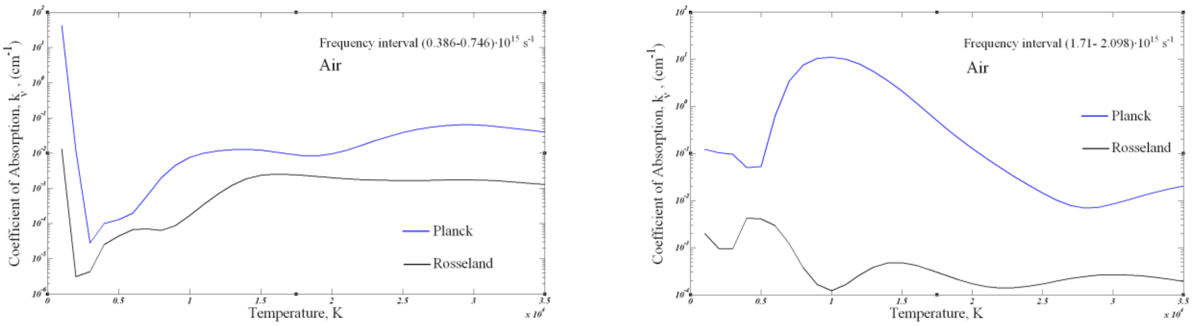
According to the absorption coefficients variation the frequency interval was divided into 11 parts given in Tab. 1.

Table 1. Limits of specific frequency intervals

interval	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
ν ($10^{15}s^{-1}$)	0.01-0.057	0.057-0.296	0.296-0.386	0.386-0.746	0.746-0.986	0.986-1.71	1.71-2.098	2.098-2.64	2.64-2.997	2.997-4.49	4.49-10

Two types of average absorption coefficients have been calculated for temperatures $T \in (1\,000, 35\,000)$ K at the air plasma pressure $p=10^5$ Pa in frequency intervals given in Tab. 1 – the Planck mean (30) and the Rosseland mean (29).

There are examples of these mean absorption coefficients of air plasma for frequency intervals $(0.386\text{-}0.746)\times10^{15}s^{-1}$ and $(1.71\text{-}2.098)\times10^{15}s^{-1}$ in Fig. 2.



a) b)

Fig. 2. Planck and Rosseland mean absorption coefficients of air thermal plasma in the two corresponding frequency intervals (a) 4 and b) 7 from Tab.1).

The use of Rosseland and Planck mean absorption coefficients is only strictly appropriate in limiting circumstances. In the multigroup method, the splitting of the whole frequency interval has to be made according to absorption coefficients frequency dependence. For frequency groups with low values of absorption coefficients, the use of Planck mean is appropriate; for groups with high values of absorption coefficients, the Rosseland mean is more suitable. In our case, for groups 1-9 the Planck mean gives better results, in the groups 10, 11 the Rosseland mean is more appropriate.

7.1.1. ISOTHERMAL PLASMA CYLINDER

In case of cylindrically symmetrical plasma the multigroup diffusion equation (28) depends only on one variable – radial range *r*

$$\mathrm{div}\left(-\frac{1}{3\bar{\kappa}_n}\,\mathrm{grad}\,u_n(r)\right)+\bar{\kappa}_n u_n(r)=\bar{\kappa}_n 4\pi B_n\,. \tag{31}$$

with $u_n(\vec{r})\equiv cU_n(\vec{r})$ and $B_n(\vec{r})=\int_{\nu_{n-1}}^{\nu_n}B(\nu)\,\mathrm{d}\nu$.

Let's express div(grad *u*) in cylindrical coordinate system

$$\frac{1}{r}\frac{\partial}{\partial r}\left(-\frac{1}{3\bar{\kappa}_n}\,r\,\frac{\partial u_n(r)}{\partial r}\right)+\bar{\kappa}_n u_n(r)=\bar{\kappa}_n 4\pi B_n\,. \tag{32}$$

Due to the fact that functions $\bar{\kappa}_n$ and B_n are dependent on the arc temperature and it decreases from the axis to the edge they are usually regarded as radial range functions. If we assume that plasma is isothermal, i.e. the arc temperature remains constant, functions $\bar{\kappa}_n$ and B_n also remain constant for the current solution of the equation (31), resp. (32).

Let's modify the equation (32) to the Bessel equation

$$r^2\frac{\partial^2 u_n(r)}{\partial r^2}+r\frac{\partial u_n(r)}{\partial r}-3\bar{\kappa}_n^2 r^2 u_n(r)=-3\bar{\kappa}_n^2 r^2\,4\pi B_n\,. \tag{33}$$

The solution of this equation with the boundary conditions [8]

$$\left.\frac{\partial u_n(r)}{\partial r}\right|_{r=0}=0\,,\qquad \left.\frac{1}{3\bar{\kappa}_n}\frac{\partial u_n(r)}{\partial r}\right|_{r=R}=-\frac{u_n(R)}{2} \tag{34}$$

is given by

$$u_n(r)=-\frac{4\pi\sqrt{3}\,B_n}{2\,J_1\left(\sqrt{3}\,\bar{\kappa}_n R\right)+\sqrt{3}\,J_0\left(\sqrt{3}\,\bar{\kappa}_n R\right)}J_0\left(\sqrt{3}\,\bar{\kappa}_n r\right)+4\pi B_n \tag{35}$$

where $J_0(x)$, $J_1(x)$ are modified Bessel functions of the first kind.

Required flux divergence is

$$\begin{aligned}\mathrm{div}\,\vec{W}_n(r)&=4\pi\,\bar{\kappa}_n B_n-\bar{\kappa}_n u_n(r)=\\&=\frac{4\pi\sqrt{3}\,\bar{\kappa}_n B_n}{2\,J_1\left(\sqrt{3}\,\bar{\kappa}_n R\right)+\sqrt{3}\,J_0\left(\sqrt{3}\bar{\kappa}_n R\right)}J_0\left(\sqrt{3}\,\bar{\kappa}_n r\right).\end{aligned} \tag{36}$$

To calculate the mean divergence of the whole cross section one is supposed to sum up the parts of the cyclic cross sections of the plasmatic cylinder on the whole surface and to divide into the same one

$$\left(w_{avg}\right)_n = \frac{2\pi}{\pi R^2}\int_0^R r \,\mathrm{div}\, \vec{W}_n(r)\mathrm{d}r = \\ = \frac{2}{R}\frac{4\pi B_n}{2\, J_1\left(\sqrt{3}\bar{\kappa}_n R\right) + \sqrt{3}\, J_0\left(\sqrt{3}\,\bar{\kappa}_n R\right)} J_1\left(\sqrt{3}\bar{\kappa}_n R\right). \tag{37}$$

Summing over all frequency groups gives the net emission

$$\mathrm{div}\,\vec{W}_R = w_{avg} = \sum_n \left(w_{avg}\right)_n = 4\pi\varepsilon_N\,, \tag{38}$$

where ε_N is the net emission coefficient.

The net emission coefficient for the isothermal plasma cylinder with radius R is given by [11]

$$\varepsilon_N = \int_0^\infty B(\nu)\kappa_\nu \exp(-\kappa_\nu R)\mathrm{d}\nu \tag{39}$$

and can be calculated with direct integration over the real spectrum.

Equations (37), (38) has been solved for isothermal air plasma cylinder at the pressure of 10^5 Pa, in temperature range (10 000 – 30 000) K, and for various plasma radius (0.01; 0.1; 1; 10) cm. The frequency interval $(0.01-6)\times10^{15}\,\mathrm{s}^{-1}$ has been divided into 11 frequency groups which are given in Table 1. Comparison of the net emission (39) calculated using different mean values of absorption coefficient is presented in Fig. 3 for four different radii of the plasma cylinder.

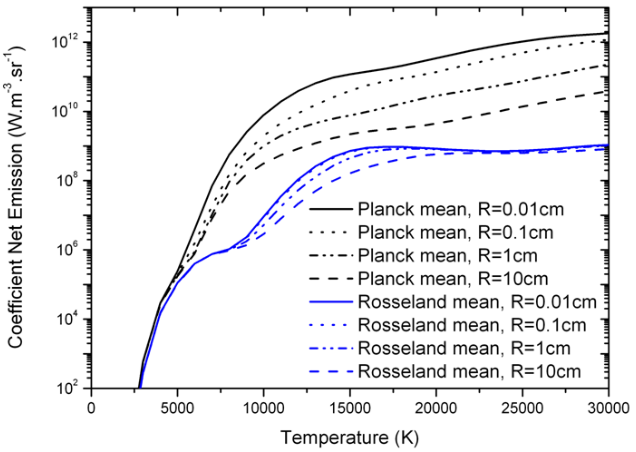


Fig. 3. Net emission of air isothermal plasma cylinder as a function of temperature for various thicknesses of the plasma.

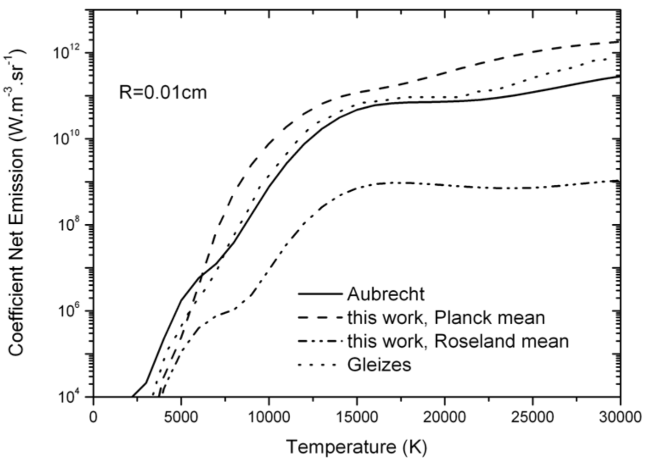


Fig. 4. Comparison of net emission coefficient of air with results of of Aubrecht [12] and Gleizes [13].

It can be seen that Rosseland averaging leads to lower values of the net emission which follows from the fact that Rosseland means underestimate the influence from the absorption peaks in the real absorption spectrum.

In Fig. 4 comparison is made of our calculations of net emission coefficient in air arc plasma of two radii with the results of Aubrecht [12] and Gleizes [13]. Planck averaging gives the results which are in satisfactory agreement with calculations of the other authors. Discrepancies between our results and those of Aubrecht and Gleizes can be explained by different approximate methods of calculation. Both Aubrecht and Gleizes use the method of the net emission coefficient with the integration over the real absorption spectrum.

7.1.2. PLASMA WITH GIVEN TEMPERATURE PROFILE

1D axisymmetric plasma column of radius *R* defined by the temperature radial profile *T(r)* and the constant pressure *p* was considered. The medium is assumed to be at local thermodynamic equilibrium and the temperature profile completely defines the local composition and enables radiative transfer calculations. The plasma column is assumed to be surrounded by a cold black medium, which means that radiative intensity incoming into the plasma is negligible and all the outcoming radiation at the interface $r = R$ is absorbed by the surrounding medium.

The prescribed temperature profile is given by [14]

$$T(r) = \left\{ \left[T_0^{1/10} - T_w^{1/10} \right] \times \left[1 - \left(\frac{r}{R} \right)^2 \right] + T_w^{1/10} \right\}^{10},$$

$$T_0 = 25000K, \quad T_w = 300K, \qquad (40)$$

where T_0 is the temperature at the arc axes, T_w is the temperature at the plasma edge, R is the radius of the plasma cylinder, and r is the radial distance from the arc axes. This type of temperature profile simulated the plasma of free burning arc.

The parameters $\bar{\kappa}_n$ and B_n in (31) are regarded as radial range functions, and the system of equations (31) must be solved numerically. The number of equations depends on the number of splitting groups. The equation (31) with boundary conditions (34) was solved for plasma cylinder of radius R = 0.3 cm with temperature profile (40) and for various mean absorption coefficients. A commercial *Finite_Element Partial Differential Equations* solver, *FlexPDE* [15] was used. Calculated net emission (divergence of radiation flux) and radiation flux are shown in Figs. 5 and 6, resp., and compared with results obtained by the method of partial characteristics (MPC) [14]. For the net emission, good agreement with MPC has been obtained at the arc axis for Planck averaging. The P_1-approximation overestimates the absorption of the emitted energy at the arc edge (the negative part of the net emission). The Rosseland approach underestimates the emission seriously. The difference comes mainly from the way they handle the peaks in the spectrum.

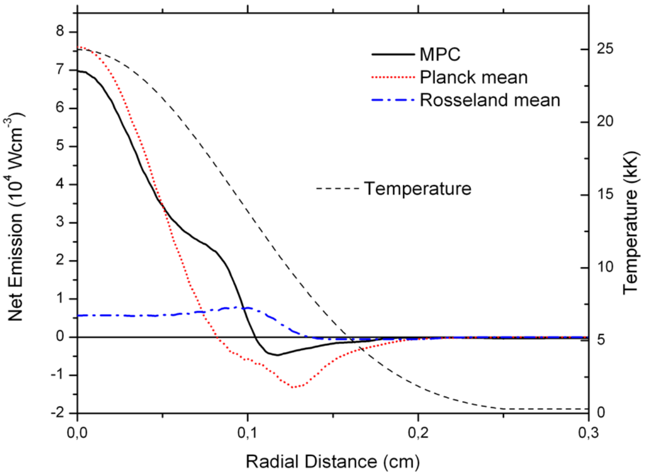


Fig. 5. Net emission in P_1-approximation for various spectral averaging; comparison with results of the method of partial characteristics [14].

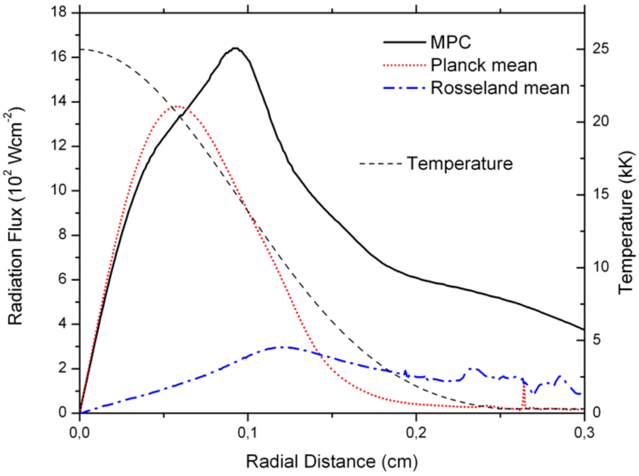


Fig.6. Radiation flux in P_1-approximation for various spectral averaging; comparison with results of the method of partial characteristics [14].

7.2. SF_6 PLASMA

SF_6 (sulphur hexafluoride) is considered as one of the best quenching media in mid and high voltage circuit breakers. Equilibrium composition of thermal plasma SF_6 was computed using *Tmdgas* computer code ([3], [4]). Absorption coefficients of SF_6 plasma at the pressure of 0.5 MPa and for temperatures of 5 000 K and 20 000 K are shown in Fig. 7. In calculation of absorption spectrum S, F neutral atoms, and S^+, S^{+2}, S^{+3}, F^+, F^{+2} ions were taken into account. Contribution of SF_6 molecules was included using their experimentally measured absorption cross sections [16].

The absorption coefficients were calculated for the frequency range $(0.01\text{-}10)\times10^{15}$ s^{-1}. This range was divided to specific intervals. There is division of frequency range in Tab.1.

Then Planck and Rosseland mean absorption coefficients of SF_6 plasma have been calculated for 11 specific frequency intervals for pressure from 0.5 to 5 MPa. Comparison of two different mean values for two selected frequency intervals $(0.386\text{-}0.746)\times10^{15}$ s^{-1} and $(1.71\text{-}2.098)\times10^{15}$ s^{-1} of SF_6 plasma at a pressure of 0.5 MPa is given in the Fig. 8.

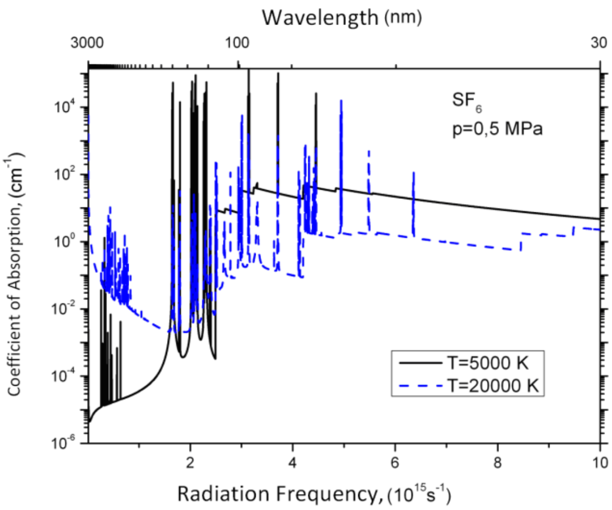
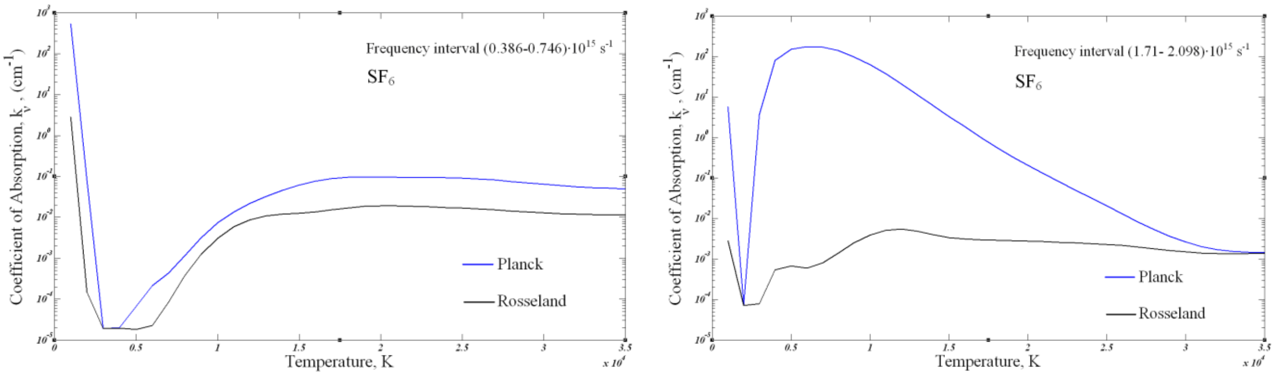


Fig. 7. Absorption coefficient of SF_6 thermal plasma as a function of frequency for two temperatures.



a) b)

Fig. 8. Planck and Rosseland mean absorption coefficients of SF_6 plasma in the two corresponding frequency intervals (a) 4 and b) 7 from Tab.2).

7.2.1. ISOTHERMAL PLASMA CYLINDER

Afterwards, using different mean values of absorption coefficient, net emission coefficients (37), (38) were calculated. In the Fig. 9, a comparison is given of the net emission coefficient calculated using various averaging methods with results of Aubrecht [12]. As can be expected from the definition of Planck and Rosseland means, for low values of plasma radius (R = 0.01 cm) the Planck mean gives good agreement with other data of net emission coefficients, with increasing plasma thickness the emission overestimation in the Planck approach becomes evident.

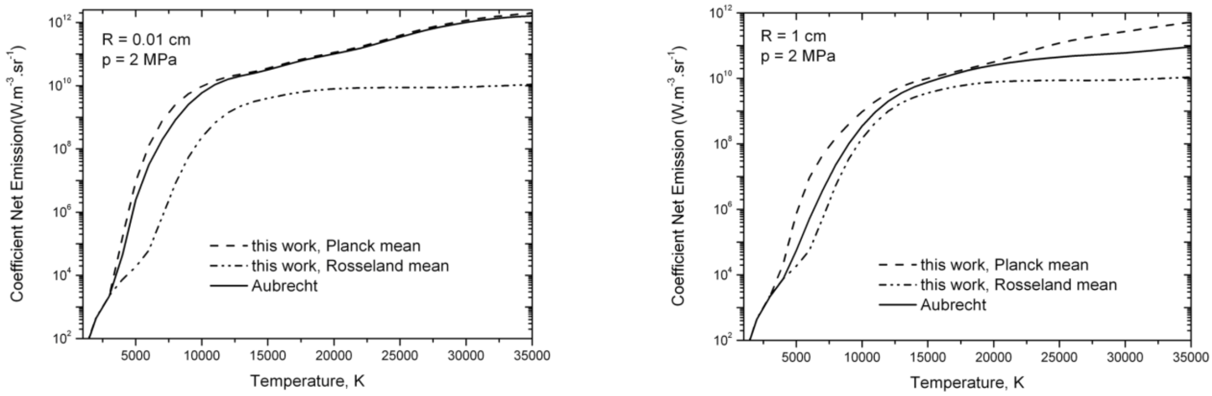


Fig. 9. Net emission coefficients of SF_6 plasma with radius of 0.01 cm and 1 cm as a function of temperature for various absorption means. Comparison with results of Aubrecht [12].

Comparison of the net emission coefficients for five different radii of the plasma cylinder at a pressure of 1 MPa is presented in the Fig. 10. Calculations were performed using Planck mean absorption coefficients. The zero radius corresponds to omitting of self-absorption. Besides the temperature variation the plasma thickness has great influence on the radiation emission.

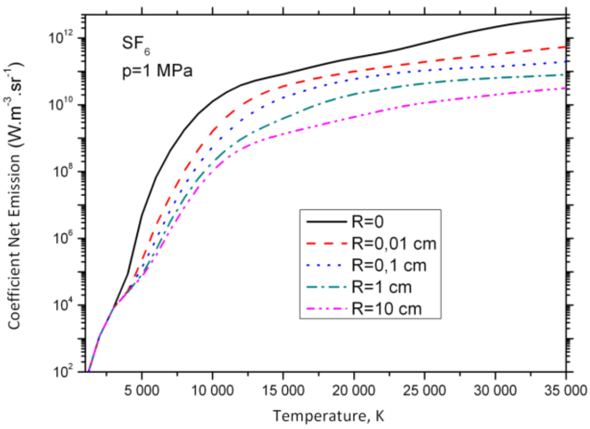


Fig. 10. Coefficient net emission of SF_6 plasma for various radii, Planck mean.

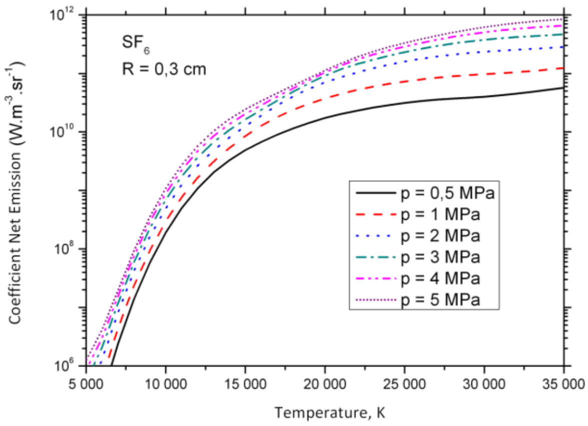


Fig. 11. Coefficient net emission of SF_6 plasma for various pressures, Planck mean.

The influence of plasma pressure on the values of the net emission coefficients calculated using Planck averaging method is shown in the Fig. 11. Net emission coefficients are presented for plasma radius 0.3 cm as a function of the plasma temperature for the pressure up to 5 MPa. Again the Planck mean absorption coefficients were used. The pressure increasing leads to higher values of the net emission coefficients at all temperatures. The net emission coefficients are proportional to population densities of energy levels in atoms and ions which increase with pressure.

7.2.2. PLASMA WITH GIVEN TEMPERATURE PROFILE

Similarly to the air plasma, a 1D axisymmetric plasma column of radius *R* defined by the temperature radial profile *T(r)* and the constant pressure *p* was considered. The prescribed temperature profile is assumed to be parabolic and is given by [5]

$$T(r) = [T_0 - T_w] \times \left[1 - \left(\frac{r}{R}\right)^2\right] + T_w,$$

$$T_0 = 20000K, \quad T_w = 300K, \qquad (41)$$

where T_0 is the temperature at the arc axes, T_w is the temperature at the plasma edge, *R* is the radius of the plasma cylinder, and *r* is the radial distance from the arc axes.

P_1-approximation was used for calculation of radiation characteristics using Planck mean, Rosseland mean, and also their combination (Planck mean for groups 1 – 9 from Tab. 1, Rosseland mean for groups 10 and 11). The equation (31) with boundary conditions (34) was solved using *FlexPDE* solver [15]. The Figs. 12 and 13 show results of the net emission and the radiation flux at the pressure of 0.5 MPa and for the plasma radius of 0.25 cm; various mean absorption coefficients were used. Rosseland averaging gives very low values of emission of radiation in hot parts of the plasma, and also neglects the absorption of radiation in cold edge of the plasma cylinder (the negative values of the net emission).

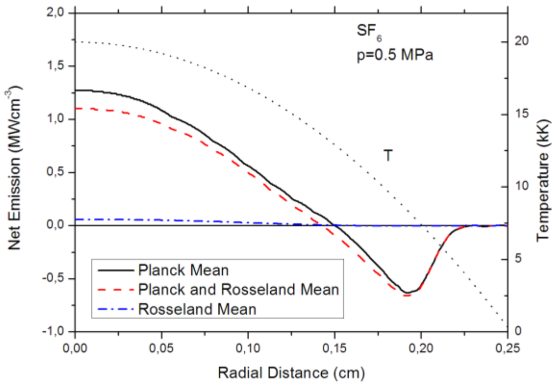


Fig. 12. Net emission in P_1-approximation for various spectral averaging.

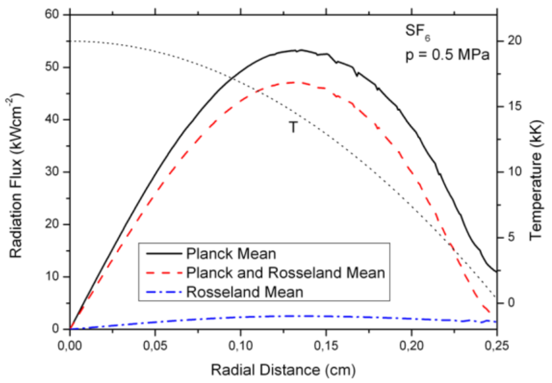


Fig. 13. Radiation flux in P_1-approximation for various spectral averaging.

7.3. MIXTURES OF SF_6 AND PTFE PLASMAS

Opening of a power electric circuit is accompanied by the formation of an electric arc (switching arc) between separated contacts. For all kind of high power circuit breakers, the basic mechanism is the extinguishing of the switching arc at the natural zero by gas convection. Widely used are SF_6 self-blast circuit breakers. The switching arc burns inside a narrow nozzle of synthetic material (PTFE – polytetrafluoroethylene – C_2F_4). Due to the high emission of radiation, the synthetic material ablates and causes a high overpressure inside the nozzle and drives the gas flow in the circuit breaker. The radiation transfer itself is the dominant energy exchange mechanism during the high current period of the switching operation.

Intensive radiation is irradiated from the hot central part of the arc and reabsorbed in cold edge of the plasma. At high temperatures, molecules are dissociated and ionized and plasma properties are determined by the composition and properties of products of dissociation and ionization. The following species were assumed: S, F, and C neutral atoms, S^+, S^{+2}, S^{+3}, F^+, F^{+2}, C^+, C^{+2}, and C^{+3} ions, and SF_6 molecules. Equilibrium compositions were computed using *Tmdgas* computer code ([3], [4]).

Absorption coefficients for various mixtures of SF_6 and PTFE plasmas for different temperature and pressure have been calculated. The comparison of absorption coefficients as a function of radiation frequency for plasmas of 100 % SF_6 and 100 % PTFE for temperature 20 000 K at pressure 0.5 MPa is given in Fig. 14.

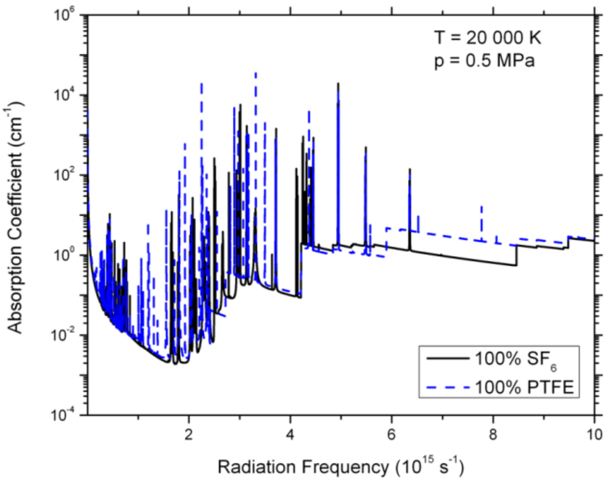
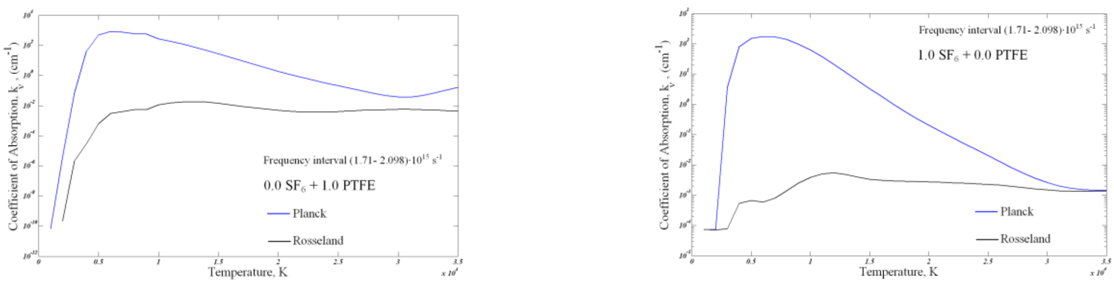


Fig. 14. Absorption coefficients of 100 % SF_6 and 100 % PTFE plasmas.

Rosseland and Planck mean absorption coefficients (30), (31) resp. have been calculated for various mixtures of SF_6 + PTFE plasmas at the plasma temperatures of 1 000 – 35 000 K. The frequency interval $(10^{13} – 10^{16})$ s^{-1} has been split into eleven frequency groups (Tab.1). Curves of absorption means for various mixtures of SF_6 and PTFE plasmas in frequency interval $(1.71 - 2.098) \times 10^{15}$ s^{-1} for pressure 0.5 MPa are shown in Fig. 15.



a) Mixtures of 0.0 SF_6 + 1.0 PTFE   b) Mixtures of 1.0 SF_6 + 0.0 PTFE

Fig. 15. Mean absorption coefficients for various mixtures of SF_6 and PTFE plasmas as a function of temperature.

By analyzing obtained results a following conclusion was made. Discrete radiation influences significantly values of Planck means; on the other hand, Rosseland mean ignores the role of lines.

Calculation of Planck and Rosseland mean absorption coefficients of various mixtures of SF_6 and PTFE plasmas was carried out for different pressure values from 0.5 MPa to 5 MPa.

The influence of admixture of PTFE on the values of mean absorption coefficients of SF_6 plasma for pressure 0.5 MPa in frequency interval $(1.71 - 2.098) \times 10^{15}$ s^{-1} is plotted in Fig. 16 and Fig. 17.

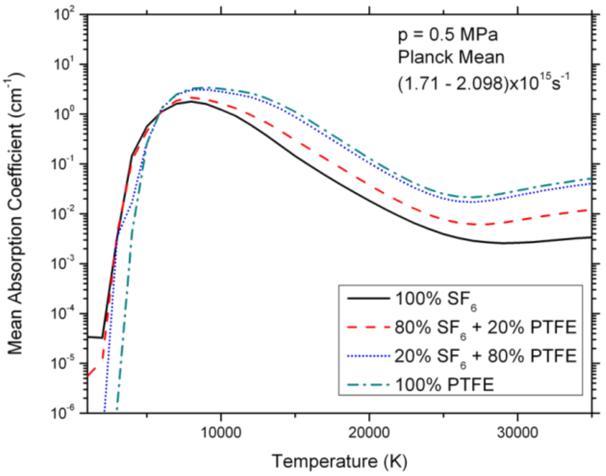


Fig. 16. Planck means as a function of temperature for various mixtures of SF_6 and PTFE.

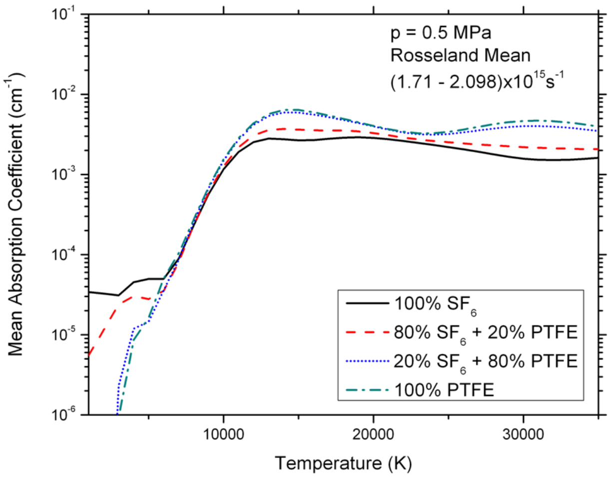


Fig. 17. Rosseland means as a function of temperature for various mixtures of SF_6 and PTFE.

7.3.1. ISOTHERMAL PLASMA CYLINDER

As in case of air and SF_6 plasma, attention was first given to isothermal plasma. The net emission coefficients have been calculated by combining equations (37), (38). Calculations have been performed for isothermal cylindrical plasma of various radii (0.01 – 10) cm in temperature range (1 000 – 35 000) K and pressures from 0.5 MPa to 5 MPa. A comparison of the net emission coefficient calculated using various averaging methods with results of Aubrecht [16] is given in the Fig. 18.

The influence of an admixture of PTFE on the values of the net emission coefficients of SF_6 plasma is given in the Fig. 19 for plasma thickness 0.1 cm and pressure 2 MPa. Differences between net emission coefficients are small. It can be explained by an approximately equivalent role of sulphur and carbon species. Both sulphur and carbon atoms and ions have similar behavior as far as radiation emission concerns.

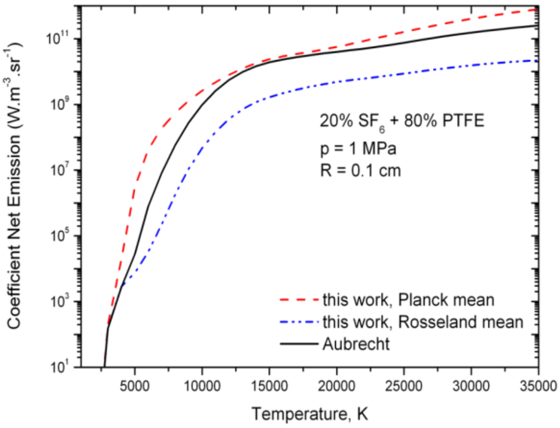


Fig. 18. Net emission coefficients as a function of temperature for various absorption means. Comparison with results of Aubrecht [16].

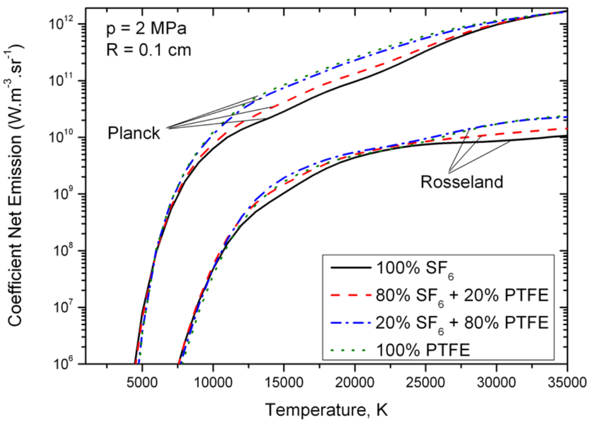


Fig. 19. Net emission coefficients of different mixtures of SF_6 and PTFE as a function of temperature at the pressure of 2 MPa for various absorption means.

7.3.2. PLASMA WITH GIVEN TEMPERATURE PROFILE

A 1D axisymmetric plasma column of radius *R* defined by the temperature radial profile *T(r)* and the constant pressure *p* was considered. The prescribed temperature profile is given by the following fitting function [17]

$$T(r) = T_w + \frac{1}{2}(T_0 - T_w)\left[\mathrm{erf}\left(\frac{0.448 + r}{0.13}\right) + \mathrm{erf}\left(\frac{0.448 - r}{0.13}\right)\right],$$

$$T_0 = 20000K, \quad T_w = 300K, \tag{42}$$

It corresponds to an axially blown arc at the pressure 1 MPa.

Fig. 20 shows results of the net emission for different averaging methods in the mixture of 80 % SF_6 and 20 % PTFE at the pressure of 1 MPa. In Figs. 21 and 22, we compare net emission for three different plasmas: pure SF_6, 80 %SF_6 + 20 % PTFE, and 20 % SF_6 + 80 % PTFE calculated using Planck and Roseland means, respectively. We can draw that Rosseland averaging gives very low values of emission of radiation in hot parts of the plasma, and also neglects the absorption of radiation in cold edge of the plasma cylinder. The admixture of PTFE leads to higher irradiation at the arc center and less absorption at the arc edge. These phenomena can be explained by the absorption coefficients behavior in the ultra violet region. The absorption of pure SF_6 plasma is higher at low temperatures (below 5 000 K) in comparison to pure PTFE plasma. At temperatures above 15 000 K, the absorption coefficients (and also emission coefficients) of pure PTFE plasma are higher in comparison to pure SF_6 plasma.

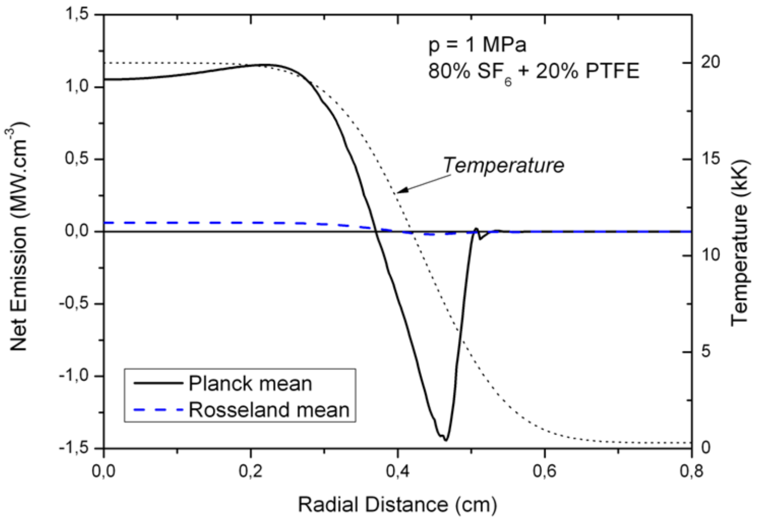


Fig. 20. Divergence of radiation flux (net emission) in the mixture of 80 % SF_6 + 20 % PTFE for various spectral averaging.

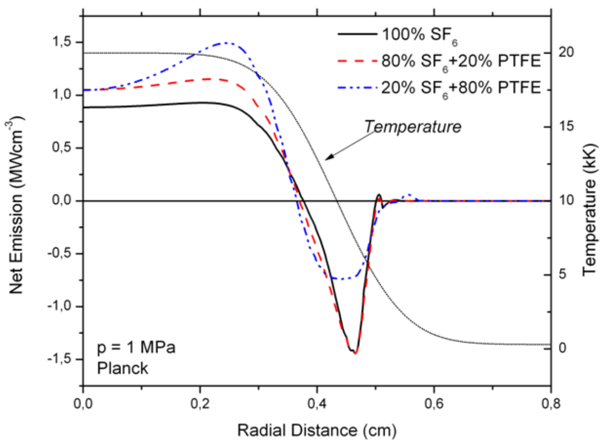


Fig. 21. Net emission as a function of radial distance in various arc plasmas calculated using Planck mean absorption coefficients.

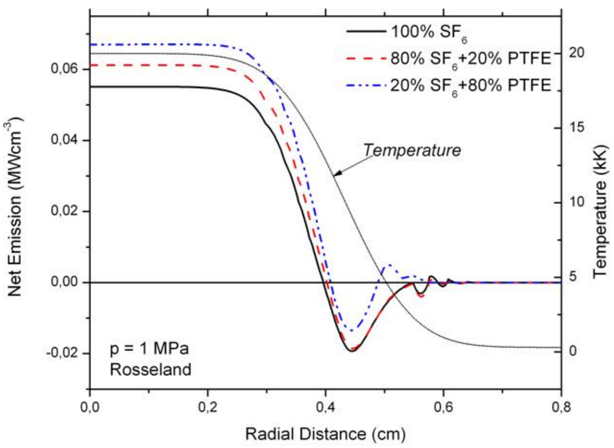


Fig. 22. Net emission as a function of radial distance in various arc plasmas calculated using Rosseland mean absorption coefficients.

The P_1-approximation is a very popular method since it reduces the equation of radiation transfer to a relatively simple elliptic partial differential equation (or more precisely in a system of several equations in case of multigroup approximation for non-grey medium) which is compatible with standard methods for the solution of the overall energy conservation equation (also a partial differential equation) and therefore does not increase the simulation time significantly. However, it must be remembered that the P_1-approximation modifies the angular distribution of the radiation and that it may leads to substantial errors in optically thin plasmas.

CONCLUSIONS

The electric arc is important in many technical applications, both because of its desired physical properties or as an unwanted result of dielectric breakdown. Experiments involving electric arcs are difficult, especially when it comes to accurately measuring the conditions inside the arc. Therefore, an extensive research has gone into the numerical modeling and simulation of arcs for various applications. Due to the high temperatures present in the arc, radiation is the dominant mechanism of energy transport and has to be included in the simulation. The proper treatment of radiative heat transfer in simulations of electric arcs is difficult for two main reasons: the radiation transfer equation itself, which is computationally expensive to solve, and the very complex nature of the absorption spectrum of an ionized gas.

The principal objective of this dissertation thesis was to investigate the radiation transfer in various arc plasmas using the approximate method of spherical harmonic functions (P_N-approximation). The method of spherical harmonics provides a vehicle to obtain an approximate solution of arbitrarily high order (i.e. accuracy), but for higher-order approximations the mathematical complexity increases extremely rapidly. Therefore, usually only the P_1-approximation is used in radiation transfer models.

In the thesis, basic principles of P_N-approximation were explained, but the main attention was given to P_3-approximation, and especially to P_1-approximation. Using the P_1-approximation the radiation characteristics of plasmas of air, SF_6, and various mixtures of SF_6 and PTFE were calculated. As the first step, the effective absorption coefficients of the plasma as a function of pressure, temperature and plasma composition in frequency range $(0.01 - 10)\times10^{15}$ s^{-1} were computed. Second, as the resulting absorption spectrum depends very strongly on the frequency, an efficient way of averaging the absorption coefficients into frequency groups had to be found. The frequency interval was split into 11 frequency groups for which both Planck and Rosseland absorption means were calculated. These absorption means were applied in following calculations.

The P_1-approximation equations were solved under assumption of isothermal plasma cylinder as well as for model temperature profiles of cylindrically symmetrical plasma. In case of isothermal plasma the equations can be solved analytically and their solution is the net emission coefficient. For plasmas with model temperature profiles the equations were solved using the solver *FlexPDE* for solution of partial differential equations. Both radiation flux and its divergence (net emission of radiation) were calculated for above mentioned plasmas.

Results of this work were compared with values of net emission coefficients, radiation flux and divergence of radiation flux, which were calculated earlier at our faculty by the method of partial characteristics. From the comparison follows that

Planck means generally overestimate the emission of radiation, and Rosseland means underestimate it. Planck means give good results only for very small plasma radius (omitting of self-absorption). Rosseland mean is a suitable approach for thick plasma (absorption dominated system). In reality, neither mean is correct in general. The simplest procedure to improve the accuracy is to use the Planck mean for frequency groups with low values of absorption coefficients and the Rosseland mean for groups with high value of absorption coefficients. This approach was partially applied in case of SF_6 plasma.

The P_1-approximation itself becomes less reliable in the optically thin limit and also, if the radiation field is anisotropic. However, it has enjoyed great popularity because of its relative simplicity and compatibility with standard methods for the solution of CFD equations. Therefore, results of this thesis are used by our colleagues from Institute of Plasma Physics, Prague, Siemens AG Corporate Technology, Germany and ABB Corporate Research, Schwitzerland in mathematical models of electric arcs.

Results of this work have been published in number of scientific articles: 8 local conference papers, 6 international conference papers (3 of them are registered in Scopus), 8 reviewed journal papers (2 registered in Scopus), and 1 impacted journal paper.

The main contribution of this work can be summarized in following main points:

- Calculation of absorption coefficients of air, SF_6 and mixtures of SF_6 and PTFE.
- Calculation of Planck and Rosseland absorption means for suitable splitting of the frequency interval.
- Solution of P_1-approximation equations for isothermal plasma cylinder and calculation of net emission coefficients.
- Solution of P_1-approximation equations for cylindrically symmetrical plasma with model temperature profiles and calculation of radiation flux and its divergence.

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CURRICULUM VITAE

Mgr. Nadezda Bogatyreva

Department of Physics, Faculty of Electrical Engineering and Communication
Brno University of Technology, 616 00 Technická 8, Brno
E-mail: nadezhda@email.cz, xbogat00@stud.feec.vutbr.cz
Web: http://www.ufyz.feec.vutbr.cz

Education and professional life

2009 – still	Technical assistant Department of Physics, Faculty of Electrical Engineering and Communication, Brno University of Technology
2008 – still	Doctoral study Specialization: "Physical Electronics and Nanotechnology" Department of Physics, Faculty of Electrical Engineering and Communication, Brno University of Technology
2006 – 2008	Master's study Specialization: "Telecommunication Systems" Department of Radio Engineering, Faculty of Instrumentation Engineering, Izhevsk State Technical University, Izhevsk, Russian Federation
2002 – 2006	Bachelor's study Specialization: "Communications facilities of the mobile objects" Department of Radio Engineering, Faculty of Instrumentation Engineering, Izhevsk State Technical University, Izhevsk, Russian Federation

Projects in BUT

2015	GACR 15-14829S Study of thermodynamic and electromagnetic processes in low voltage switching devices.
2011	GD102/09/H074 Diagnostics of material defects using the latest defectoscopic methods.
2010	FRVS 2549/2010/G1 The modernization of laboratories for non-destructive testing of components using noise spectroscopy.
	FEKT-S-10-4 Research of methodologies for improvement the optoelectronic materials and devices quality.

Active participation in conferences

2013	Physics of Switching Arc (FSO) 2013, Nové Město na Moravě, Czech Republic; 5th. Central European Symposium on Plasma Chemistry, Balatonalmádi, Hungary; Renewable sources of energy (OZE) 2013, Kouty nad Desnou, Czech Republic;
2012	12th European Plasma Conference, Bologna, Italy; Renewable sources of energy (OZE) 2012, Kouty nad Desnou, Czech Republic;
2011	Physics of Switching Arc (FSO) 2011, Nové Město na Moravě, Czech Republic;
2010	11th High-Tech Plasma Processes Conference, Brusel, Belgium; Second forum of young researchers, Izhevsk, Russian Federation;
2009	Physics of Switching Arc (FSO) 2009, Nové Město na Moravě, Czech Republic.

ABSTRACT

The main task of this work is to investigate the radiation transfer in thermal plasmas using the approximate method of spherical harmonic functions (P_N-approximation). The thesis is of theoretical nature. Main attention was given to the most popular P_1-approximation. Spectral dependence of absorption coefficients was handled by means of multigroup approximation. The computational code for calculation of radiation characteristics in isothermal plasma cylinder and in plasma cylinder with given temperature profile was prepared. Radiation characteristics of air plasma and plasma mixture of SF_6 and PTFE were calculated.

Obtained results account for data for including radiation losses into the total energy balance of arc plasma. They are used in mathematical models of electric arcs created by our collaborators from Institute of Plasma Physics Academy of Science in Prague and from abroad (ABB Corporate Research, Switzerland and Siemens AG Corporate Technology, Germany).

ABSTRAKT

Hlavním cílem práce je studium radiačního přenosu energie v termálním plazmatu pomocí aproximační metody sférických harmonických funkcí (P_N-aproximace). Práce má teoretický charakter. Pozornost je věnována především P_1-aproximaci. Spektrální závislost absorpčních koeficientů byla zpracována pomocí multigroup aproximace. Byl vytvořen výpočetní program pro výpočet radiačních charakteristik v izotermickém válcovém plazmatu a ve válcovém plazmatu s daným teplotním profilem, a vypočteny radiační charakteristiky pro plazma vzduchu a směsí SF_6 a PTFE.

Získané výsledky umožňují zahrnout radiační ztráty energie do celkové energetické bilance plazmatu elektrického oblouku. Jsou využívány v matematických modelech elektrického oblouku, které vytváří naši spolupracovníci z Ústavu fyziky plazmatu AV ČR v Praze a také ze zahraničních pracovišť (ABB Corporate Research ve Švýcarsku a Siemens AG Corporate Technology v Německu).