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ASSESSMENT OF ABSORPTION-RADIATION CHARACTERISTICS OF AN IDEAL SELECTIVE SURFACE

Ergashev Sirojiddin Fayazovich [1]***, Tojiboev Abror Kahorovich*** [1]***, Tojiboeva Muhayo Djamoldinovna*** [1]

[1] Fergana Polytechnical Institute, Fergana, Uzbekistan

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Abstract

In this article, the absorption-radiative characteristics of an ideal selective surface are studied, in particular, the possibility of obtaining high heating temperatures due to solar radiation is analyzed, a model is developed and a threshold wavelength is selected, and the effective values of absorption and emissivity for a selective surface are determined. The question of the possibility and feasibility of using spectral-selective surfaces for high-temperature heating due to solar radiation has been studied, the indicators of real selective surfaces have been determined, the average effective values of absorption-emissivity and the magnitude of the characteristics of the selective surface have been given, and the corresponding conclusions have been presented.

Keywords: *concentration, collector, solar energy, selectivity, radiated energy, absorption, receiver, black body*

Introduction

The possibility of obtaining high heating temperatures due to solar radiation is associated with such a special property of the radiant energy of the Sun as the possibility of concentrating it to very high densities, as well as with the use of spectrally selective absorption beams as special receiving surfaces. In addition, a solar concentrator should be considered not only as a means of compressing a rather rarefied flux of radiation coming from the Sun, but also as its collector-catcher and transporter. As a transporter of captured solar energy to the place of use (conversion), a solar concentrator seems, in principle, to be a structure of extreme lightness, since its surface can perform only one simple function – to reflect the sun's rays. The selectivity property of the receiver allows, in turn, to reduce the required concentration values, reduce the requirements for the accuracy of the shape of the mirror surface and its tracking of the Sun, and reduce the weight of its structure and orientation system, which is especially important for reducing the cost of the power plant.

The question of the possibility and feasibility of using spectral-selective surfaces for high-temperature heating due to solar radiation is currently attracting much attention from researchers, both abroad and in our country. The issue has not yet been sufficiently considered, and not always from a fundamentally correct position. Even the basic concepts – about the ideal selective surface, about the maximum possible heating temperature, and the application of the second law of thermodynamics and Kirchhoff's law – need clarification. Explicitly or implicitly, it is usually concluded that the selectivity property degenerates with increasing temperature, and it is unclear, at least, whether the use of the selectivity effect in high-temperature installations will be useful (Abdurakhmanov, A. A., Turaeva, U. F., Klychev, Sh. I., 2008; Avezov, R. R. 1990; Renewable energy sources. 2001).

Materials and methods

Determination of the ideal selective surface (ISS). Selecting the threshold wavelength. Solar radiation, with a good approximation, can be represented as radiation from an absolute black body (ABB) with a temperature T_s = 5800 K, for which the highest intensities occur in the spectral range $\lambda = 0.1 +$ + 2.5 mcm, where 97% of all emitted energy is concentrated. If a body absorbs maximum in this range, and has minimal emissivity in the range of its own radiation, then a significant effect is obtained (note, for example, that at heating temperature levels of 1000–1500 °K often used in power systems, the interval $\lambda = 2 + \infty$ mcm accounts for 83–73% of emitted energy) (Zahidov, R. A. 2008).

Based on the above, a suitable definition of an ideal selective surface (ISS) for the purpose of heating is its previously proposed (Zahidov, R. A., Saidov, M. S. 2009; Use of solar energy in space research, 1964) definition as a surface having $a_{s\lambda} = \mathcal{E}_\lambda = I$ in the wavelength region $\lambda < \lambda_{lim}$ and $a_{s\lambda} = \mathcal{E}_\lambda = 0$ in the region $\lambda \geq \lambda_{por}$, however, with the addition that the value of λ_{lim} is selected each time as optimal (depending on the density of the incident solar radiation flux and the operating temperature of the surface), providing the maximum temperature effect.

When the radiation receiver (concentrator-receiver system) operates in a vacuum, the calculated expression for $\lambda_{lim.opt}$ can be found from the condition of obtaining the extremum (maximum) of the expression:

$$P_c = \frac{\int_0^{\lambda \lim} r(\lambda T_s)\, d\lambda}{n} - \int_0^{\lambda \lim} r(\lambda T_n)\, d\lambda \qquad (1)$$

The maximum value of useful energy P_c will be when:

$$\frac{dP}{d\lambda \lim} = 0 \, \textit{that is}, \text{ when}$$

$$\frac{r(\lambda_{\lim} T_s)}{n} - r(\lambda_{\lim} T_n) = 0 \qquad (2)$$

After performing the transformations, we get:

$$n = \frac{e^{c_2/(\lambda_{\lim})opt * T_n} - 1}{e^{c_2/(\lambda_{\lim})opt * T_s} - 1} \qquad (3)$$

In these expressions T_n – temperature of the surface receiving radiation; T_c – average temperature of the solar surface; C_2 – quantities included in the Planck formula;

$r\left(\lambda T_s\right) r\left(\lambda T_n\right)$ n is the coefficient of attenuation of the solar radiation density at a given point in space compared to that directly at the surface of the Sun.

Relationship (3) can also be presented as:

$$T_n = \frac{C_2}{(\lambda_{\lim})_{opt} \ln\{n[e^{c_2/(\lambda_{\lim})_{opt} * T_s} - 1] + 1} \qquad (4)$$

Equations (3) and (4) give a relationship between three quantities: $n, (\lambda_{\lim})_{opt}$ and – temperature of the surface receiving radiation. Both Equations are relatively transcendental and do not allow one to accurately represent them explicitly as a function of magnitudes and n. It is possible to write an iterative type explicitly:

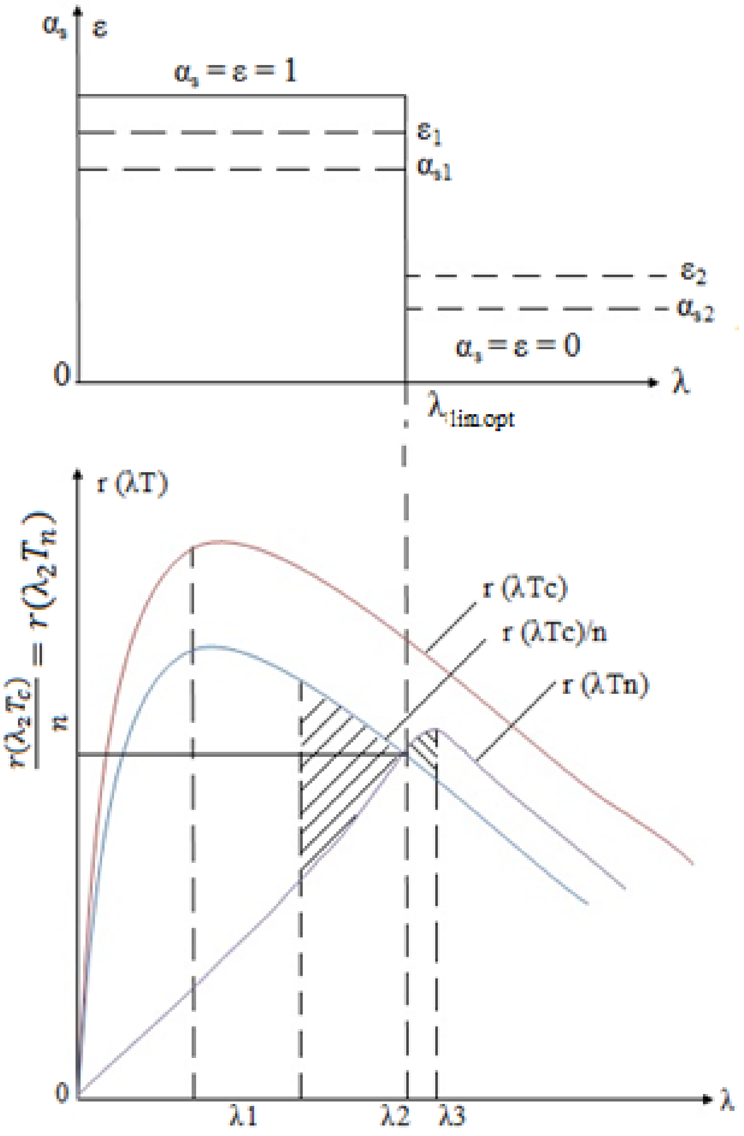
$$T_n (\lambda_{\lim})_{opt} \; n, (\lambda_{\lim})_{opt} \; T_n$$

$$(\lambda_{\lim})_{opt} = C_2 \left(\frac{1}{T_n} - \frac{1}{T_s} \right) \ln \frac{n}{\frac{n-1}{e^{C_2/\lambda_1 T_n}} + 1} \qquad (5)$$

where $\lambda_1 = C_2 \left(\frac{1}{T_n} - \frac{1}{T_s} \right) / \ln n$

Equations (3) and (4) can be obtained not only from an expression for the maximum received energy of type (2), but also in a simpler (algebraic) way, which allows for a better (simpler, more visual) representation of the expected result.

Figure 1. *Towards the representation of an ideal selective surface and determination of the value of the optimal threshold wavelength* $(\lambda_2 = \lambda_{\lim.opt})$

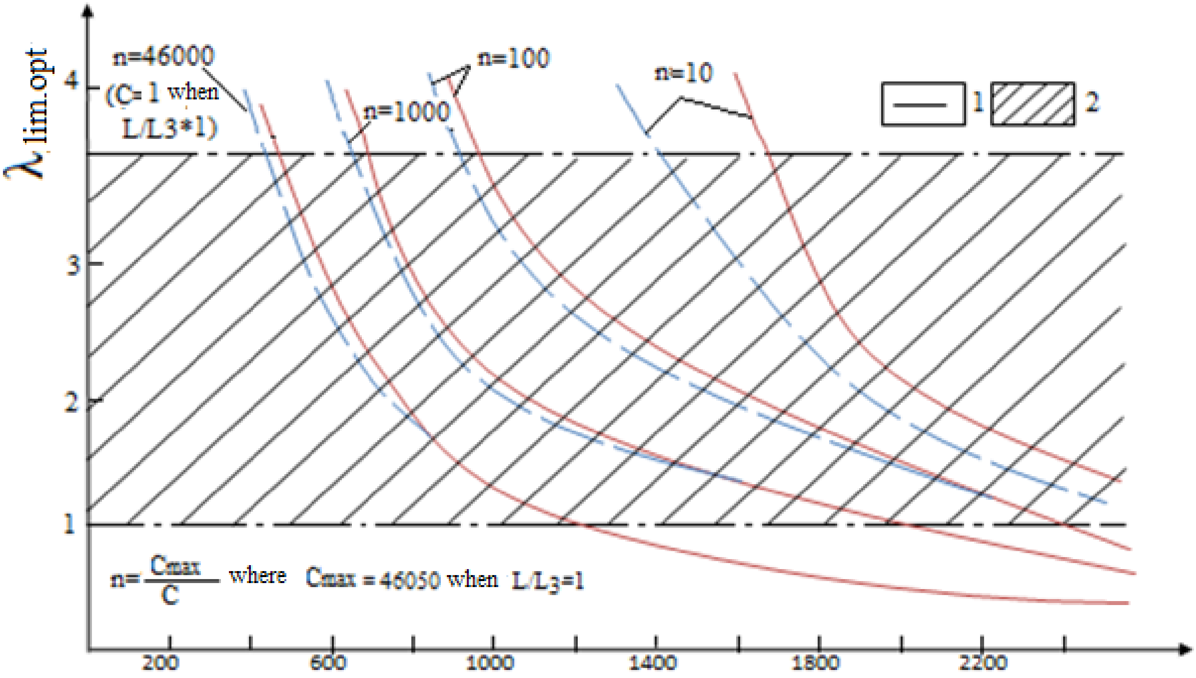


A simple graphical analysis of (Fig. 1) leads to the answer: $(\lambda_{\lim})_{opt}$ can be defined as the abscissa of the intersection point of curves 2 and 3 (i.e.). In fact, if we assume that it corresponds to a certain λ1, in this case, although the own radiation decreases, the reception of the incident energy deteriorates. Similarly, if we assume that it is equal to some $\lambda 3(\lambda_{\lim})_{opt} = \lambda_2(\lambda_{\lim})_{opt}(\lambda_{\lim})_{opt}$, then there is a loss of energy due to radiation from the absorption capacity of the receiver. Writing the equations for curves (2) and (3) according to Planck and solving them together, we obtain:

$$\frac{r(\lambda_{\lim} T_s)}{n} = r(\lambda_2 T_n)$$

Finally, i.e. expression coinciding with (3) values calculated using Equations (3) and (4) for various quantities $n = \frac{e^{c_2/(\lambda_2 T_n)} - 1}{e^{c_2/(\lambda_{2T_s})} - 1}(\lambda_{\lim})_{opt}$ T_n and n are presented in the graph in (Fig. 2). The same graph shows the values $(\lambda_{\lim})_{opt}$, calculated using the approximate formula proposed in (Klychev, Sh.I. 2004; Beckman, W., Klein, S., Duffy, J., 1982). As can be seen, in a number of practically interesting combinations of parameters, the error in the approximate determination of the value can be significant. The use of an approximate formula also complicates the general analysis of heating capabilities when using a selective receiving surface. The general pattern noticeable from the graph in (Fig. 2): a decrease in value with an increase $(\lambda_{\lim})_{opt}$ $(\lambda_{\lim})_{opt}$ Tn and a decrease in the radiation concentration.

Figure 2. *Values of the optimal threshold wavelength according to the exact formula (3) and the approximate one (Avezov, R. R. 1990; Renewable energy sources. 2001); 1 – exact value* $(\lambda_{\lim})_{opt}$ *; 2 – suitable area of application of selective surface*



Results and discussion

Turning to the (Fig. 1) in detailed: 1-curve of radiation intensity distribution over wavelengths of the solar spectrum (approximately – the radiation curve of the black body at T_s = 5800K), 2-this is the same curve with ordinates reduced by times; 3- radiation curve of the black body (on the surface of the receiver) at the temperature of the receiving surface T_n.

$$\frac{r(\lambda_{\lim} T_s)}{n} = r(\lambda_2 T_n) \tag{6}$$

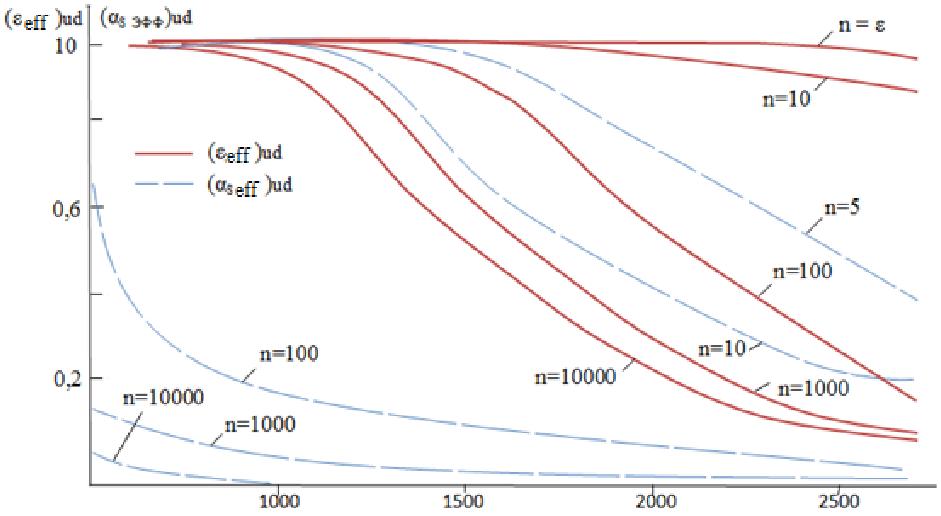
From Equations (3) and (4) a somewhat unexpected conclusion is revealed about the presence of minimum temperatures, below which the effect of radiation absorption selectivity does not appear.

Believing $(\lambda_{\lim})_{opt} \to \infty$ from expression (4) one can find that the quantityTn tends to a certain limit

$$\lim T_n =$$
$$= \lim \frac{C_2}{(\lambda_{\lim})_{opt} \ln[n(e^{c_2/(\lambda_{\lim})_{opt} {}^* T_s} - 1) + 1]} =$$
$$= \lim \frac{n\, e^{c_2/(\lambda_{\lim})opt^* T_s} - 1}{n\, e^{c_2/(\lambda_{\lim})opt^* T_n} - \frac{1}{T_s}} = \tag{7}$$
$$- \lim \left[T_s \left(1 - \frac{1}{e^{c_2/(\lambda_{\lim})opt T_s}} + \frac{1}{n e^{c_2/(\lambda_{\lim})opt T_s}} \right) \right] = \frac{T_s}{n}$$

Expression (7) determines the lower limit of the heating temperature, starting from which the property of selective radiation absorption can manifest itself. For example, to the levels of the Earth's orbit ($C_{\max} \approx$ ≈ 46000) at C = 4600 (n =10)^x the beginning of the selectivity effect corresponds to $(T_n)_{\min}$ = = 580 °K.

Figure 3. *Effective values of absorption-emitting characteristics for ISS*



Determination of effective values of absorption and emissivity for a selective surface

To determine the integral (i.e., effective) values of the absorption-emitting abilities of an ideal selective surface, we can write

$$(a_{s\,\text{эфф}})_{ud} = \frac{\int_0^{(\lambda_{\lim})_{opt}} r(\lambda T_s)\,d\lambda}{\int_0^{\infty} r(\lambda T_s)\,d\lambda};$$

$$(\varepsilon_{\text{эфф}})_{ud} = \frac{\int_0^{(\lambda_{\lim})_{opt}} r(\lambda T_n)\,d\lambda}{\int_0^{\infty} r(\lambda T_n)\,d\lambda} \qquad (8)$$

Real selective surfaces may have characteristics of change and $\mathcal{E}$ as a function of λ that are qualitatively similar to those for an ideal selective surface (ISS): in the region of a rather narrow interval of λ there may be a sharp drop in these values, which can be approximately represented as a "threshold" (Kuchkarov, A.A., Muminov, Sh.A. 2020; Yu. Yu. Pochekailov, A.V. Shashev, V.I. Yakovlev, N.A. Yakovlev, 2015). The values themselves $\alpha s1$ and $\mathcal{E}1$ (up to the threshold) turn out to be, although close to unity, but less than unity. The quantities $\alpha s2$ and $\mathcal{E}2\alpha_s$(after the threshold), turning out to be quite small, are still noticeably not equal to zero (see Fig. 1, a, b).

For such real selective surfaces, the average effective (over the spectrum) values of absorption-emissivity can be determined using the Equations:

$$(a_{s\,\text{эфф}})_p = (a_{s1} - a_{s2})\frac{\int_0^{\lambda_{\lim}} r(\lambda T_s)\,d\lambda}{\int_0^{\infty} r(\lambda T_s)\,d\lambda} + a_{s2} \qquad (9)$$

and

$$(\varepsilon_{\text{эфф}})_p = (\varepsilon_1 - \varepsilon_2)\frac{\int_0^{\lambda_{\lim}} r(\lambda T_n)\,d\lambda}{\int_0^{\infty} r(\lambda T_n)\,d\lambda} + \varepsilon_2 \qquad (10)$$

These numbers are quite realistic. The values Cav=4000+8000 can be obtained, in particular, for projector-type glass mirrors.

For the real selective surface (RSS) represented in this way, as well as for the ISP, the value of the optimal threshold wavelength is determined by relations (3), (4).

Figure (4) shows the calculated values of the effective absorption-emissive abilities of the ISS depending on the heating temperature at different values of the incident radiation density. With increasing heating temperature values $(\alpha s\ eff)_{ud}$ and $(\mathcal{E}\ \text{eff})_{ud}$ decreases and tends to zero at $T_n \to T_s$ (in accordance with Kirchhoff's law. An important characteristic of the selective surface is the value. Let's call it the selectivity parameter.

$\Pi_c = \dfrac{a_{s\,\text{эфф}}}{\varepsilon_{\text{эфф}}}$ For an ideal selective surface

$$(\Pi_c)_{u\partial} = \frac{\int_a^{(\lambda_{\lim})_{opt}} r(\lambda T_s)\,d\lambda}{\int_a^{(\lambda_{\lim})_{opt}} r(\lambda T_n)\,d\lambda}\left(\frac{T_n}{T_s}\right)^4 \qquad (11)$$

Figure 4. *The value of the selectivity parameter* $\left(P_s\right)_{id} = \frac{(a_{s\,eff})_{u\partial}}{(\varepsilon_{eff})_{u\partial}}$ *for an ideally selective surface at different concentration values and different receiver temperatures*

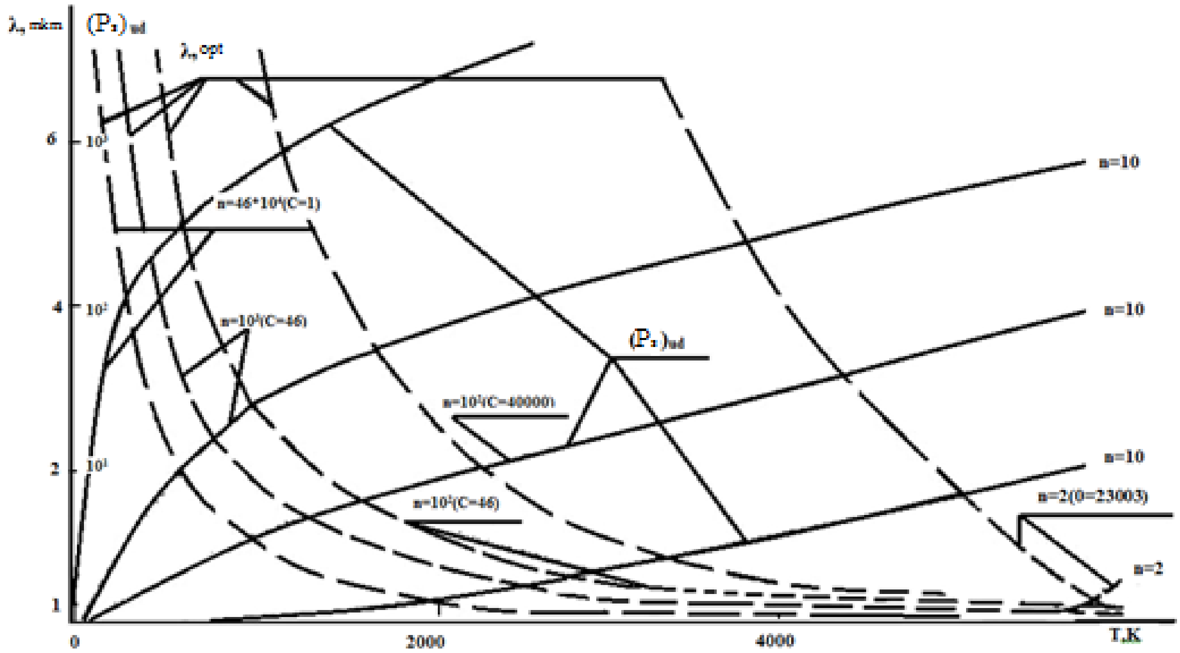
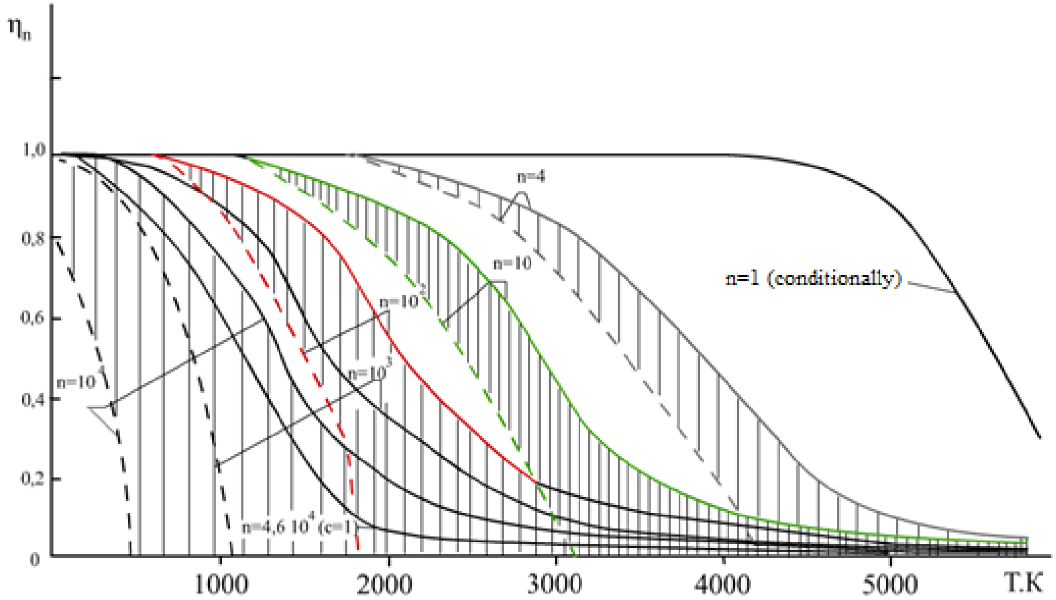


Figure 5. *Possible efficiency values concentrator-receiver systems in the case of an ideal spectral-selective surface* $\eta_R = 1$*, 1-ISS; 2- ABB (*$\alpha_s = \mathcal{E} = 1$*)*



Let us find out for ISS the nature of the change in P_s depending on temperature. As established above, the lower level of heating temperature, where the properties of the ISS are still preserved, corresponds to $\left(T_n\right)_{\min} = \frac{T_n}{n}$ and $P_s = 1$. With increasing temperature, as the results of calculations show, Fig. (5), the possible values of the parameter Π_c for the ISS increase, reaching the highest values in the absence of radiation concentration and when $T_n \rightarrow T_s$ tends. The course of the curves on the graph in (Fig. (5)) predicts that, apparently, the limiting value of P_s for ISS at $T_n = T_s$ has the value $P = n$. This is shown quite strictly below.

Our term, referred to as the general criterion, determines the properties of the selective surface.

Conclusions

The results of studies on the absorption-emissivity characteristics of an ideal selective surface show that correctly designed thermal insulating material, threshold wavelength and effective valuesof absorption and emissivity sensitively affect the efficiency of solar energy installations.

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Contact: abrortak78@mail.ru