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Research Article

# Thermodynamic Analysis of the Concentration Process of Solar Radiation

**Ryszard Petela***

Independent Scientist, Calgary, Canada

## Abstract

Extremely rarefied but high-temperature solar radiation energy is nowadays commonly concentrated to produce a high-temperature heat source. The article is a contribution to theoretical considerations on the process of concentration of solar radiation. The process of concentration of extraterrestrial solar radiation was subjected to thermodynamic analysis and the energetic, entropic and exergetic points of view were taken into account. An imaginary model of concentration was defined, which allowed the development of thermodynamic analyses of the concentration process. In the model, concentrated solar radiation irradiates the absorbing surface, the temperature of which is controlled by the intensity of cooling. The newly revealed values of temperature (7134 K) of the Sun's surface and its energetic and exergetic emissivity (0.431 and 0426, respectively) were used in the analyses. With the use of model equations, the relationship between the ratio of radiation concentration, temperature and emissivity of the absorption surface, cooling intensity, absorbed heat, ambient temperature, and energy and exergetic efficiency of the concentration process was determined. Entropy analysis confirmed that the concentration limit temperature is equal to the temperature of the Sun's surface. Examples of energy and exergetic balances of the concentration process, illustrated by band diagrams, showed the percentage share of energy and exergy fluxes. In contrast to the energy balance showing no energy loss, the exergy balance showed a significantly large loss of exergy due to the irreversibility of the process. The components of this irreversibility have been identified, which are the absorption of solar radiation and the much lower irreversibility of the emission of the heated surface.

## Keywords

Solar Thermal Radiation, Concentration of Solar Radiation, Concentration Ratio, Temperature Concentration Limit, Band Diagram of Concentration Process, Irreversibility of Radiation Concentration, Energetic Efficiency of Concentration, Exergetic Efficiency of Concentration

## 1. Introduction

Solar radiation has a high temperature, but it is very diluted [1]. By concentrating this radiation, it is possible to obtain a source of high-temperature source, which can be used in many processes [2]. Solar radiation concentration is discussed in Chapter 7 of [3]. It was assumed that the radiation comes from the black surface of the Sun (energetic emissivity $\varepsilon = 100\%$) with a temperature of about 6000 K. However, recent insight [4] into the temperature of the Sun surface has revealed that the temperature level is at least 7134 K and that the surface is not perfectly black, but that its energetic emissivity is at most

*Corresponding author: petelar@telus.net (Ryszard Petela)

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$\varepsilon$ = 43.1% and its exergetic emissivity is at most $\varepsilon_{b,S}$ = 42.6%, (the concept of exergetic emissivity was introduced in [5]). This article appropriately updates the considerations [3] on the concentration of solar radiation, using the newly revealed temperature and the energetic and exergetic emissivity of the Sun's surface.

Various technical, economic and other problems of solar radiation concentration are discussed in many publications. A descriptive overview of the problems associated with this concentration process is presented [7]. The possibility of generating electricity using solar radiation is discussed [8]. The publication [9] reviews the basic principles of solar energy concentration, including optical processes, solar radiation concentration limits, thermodynamic approaches to electricity generation, including the second law of thermodynamics, optimization of the overall system efficiency depending on the operating temperature and the size of the receiver hole. The publication [9] also discusses the thermoeconomics and optimization in design. A forward-looking paper [10] discusses the trend of developing efficient concentration of solar energy systems by improving operating temperatures to over 700 ℃, as well as technologies for efficient solar energy storage, heat storage and power generation at such temperatures.

Some specific aspects were also considered, such as the efficiency of concentrating systems [11], numerical simulation of the absorption of concentrated solar energy by a packed silicon carbide bed [12], future prospects for solar energy and thermochemical fuel production [13], the possibility of obtaining a fine-grained microstructure of molten material in a solar furnace to improve its mechanical and dielectric properties [14], and a review of technical, technological and economic problems associated with the use of concentrated solar radiation [15].

This paper is a contribution to the general theoretical problems of the process of concentration of undiluted extraterrestrial solar radiation. The presented thermodynamic analysis covers the energetic and exergetic balance of the radiation concentration process as well as the energetic and exergetic efficiency of the process, using the newly revealed values of emissivity and temperature of the Sun's surface [4]. A simplified thermodynamic model of the concentration process is formulated, along with a set of mathematical formulas that allow for the analysis of the influence of the assumed parameters on the results of the concentration process.

The direct conclusions from the presented considerations can be used for concentration devices located above the Earth's atmosphere. Considerations about the concentration of solar radiation on the Earth's surface are complicated because the atmosphere significantly changes the solid angle of radiation propagation, and the spectrum of radiation depends on the weather, season, time of day and geographical location. Therefore, the conclusions of this paper for the conditions prevailing on the Earth's surface can be limited only to a qualitative estimation of the parameters of the concentration process.

## 2. Simplified Radiation Concentration Model

A simplified model is usually created in the form of an imaginary object that simulates a real process and allows for an easy way to formulate mathematical equations that describe the process in a quantitative way. Such a radiation concentration model, originally proposed by Petela [3], was here developed here to analyze the concentration of extraterrestrial solar radiation coming from the Sun's surface with a constant temperature of $T_S$=7134 K, energetic emissivity ε=0.431 and exergetic emissivity $\varepsilon_{B,S}$=0.426. The model consists of the three surfaces shown in Figure 1.

The first surface, with an area of $A_S$, simulating the surface of the Sun with its properties experienced by the Earth, is a certain imaginary surface that represents the radiation energy $E_S$, coming from the Sun. (The symbol $A$ used for any surface can mean its area and the designation of this surface). The surface $A_S$ reflects radiation from surface $A$ at a very small solid angle (like the far Sun), so the energy of these reflections can be ignored.

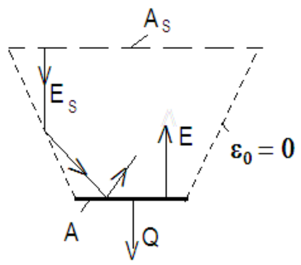


***Figure 1.*** *Scheme of Radiation Concentration.*

The second surface of area $A$ simulates the acquisition of usable heat in the concentration process. The surface area ratio $A_S$ and $A$ is the concentration ratio, $a_S = A_S/A$. Surface $A$, irradiated only by the surface $A_S$, partially reflects solar radiation, emits its own energy $E$, and is cooled by the usable heat $Q$, W. Surface $A$ is gray, with an emissivity of $\varepsilon$. The temperature $T$ of surface $A$ is controlled by cooling at certain heat rate $q$, W/m$^2$.

The vacuum space between the two surfaces ($A_S$ and $A$) is enclosed by a third surface, simulating a concentration device. This surface is the side of an inverted truncated cone and is perfectly mirror-like ($\varepsilon_0$=0) on both sides. Such an assumption means that there is no penetration of radiation from the environment and no escape of radiation from surfaces $A_S$ to the environment. The cone should be high enough so that all the radiation of surface $A_S$ goes only to the surface $A$. In practice, for example, the surface $A_S$ can represent all mirrors directing solar radiation to a certain surface $A$, from which heat is used to generate steam for a power plant.

The real energy ***e*** emitted from the surface of the Sun propagates evenly in all directions of the hemisphere, but reaches the Earth only within the solid angle ω=2.16×10$^{-5}$×π. The portion $e_E$, W/m$^2$, of solar emission reaching the Earth is calculated as follow [3]:

$$e_E = \frac{e}{\pi}\ 2.16 \times 10^{-5}\pi, \quad (1)$$

where the emission $e$, W/m$^2$, of the Sun's black surface at temperature $T_S$, is calculated according to the Stefan-Boltzmann formula [3]:

$$e = \sigma\ T_S^4, \quad (2)$$

where σ = 5.6693×10$^{-8}$ W/(m$^2$ K$^4$) is the Boltzmann constant for black radiation, and $T_S$, in K, is the temperature of the Sun's surface. The exergy $b_E$ of solar radiation reaching the Earth can be calculated using the formula analogous to (1), in which instead of $e$, the exergy $b$, W/m$^2$, for a black surface is introduced:

$$b_E = \frac{b}{\pi}\ 2.16 \times 10^{-5}\pi, \quad (3)$$

where $b$ is expressed by the Petela formula [3]:

$$b = \frac{\sigma}{3}\ (3\ T_S^4 +\ T_0^4 - 4\ T_0\ T_S^3), \quad (4)$$

where $T_0$, K, is the ambient temperature.

In the study of radiation processes, the energy or exergy balance of the radiating surface can be used. In this case, the balanced system is very simple, since it is a layer of infinitesimal volume in which nothing is accumulated and the energy supplied is always equal only to the energy carried out. Thus, the energy balance of surface $A$ considers the solar energy supplied to this surface, which is equal to its reflected part, the energy emitted by surface $A$ and the absorbed heat. Thus:

$$2.16 \times 10^{-5}\ A_S\ \varepsilon_S\ \sigma\ T_S^4 = 2.16 \times 10^{-5}\ A_S(1 - \varepsilon)\ \varepsilon_S\ \sigma\ T_S^4 + A\ \varepsilon\ \sigma\ T^4 + A\ q, \quad (5)$$

where $\varepsilon$ and $\varepsilon_S$ is the energetic emissivity of surface A and $A_S$, respectively, and $q$ W/m$^2$ is the heat rate at surface A. The total heat $Q$, W, extracted from surface $A$:

$$Q = \frac{A_S}{a_S}\, q\,. \quad (6)$$

The heat rate $q$ is an important variable that strongly influences the temperature $T$ of the surface A and thus controls the utilization of concentrated radiation. The heat rate can be determined by designing the coolant flow rate and the temperature differences in the heat exchanger used as a usable heat source. The heat rate can be designed with a value in a wide range. For example, the coefficient of heat transfer from the surface to the fluid can range from a few to 100,000 W/m$^2$, [16].

The energetic efficiency $\eta_E$ of solar radiation concentration can be determined as the ratio of the absorbed heat $Q$ to the solar radiation energy reaching the surface $A$:

$$\eta_E = \frac{Q}{2.16\times10^{-5}\ A_S\ \varepsilon_S\ \sigma\ T_S^4}. \quad (7)$$

For comparison, the exergetic efficiency $\eta_B$ can also be considered based on the following definition:

$$\eta_B = \frac{B_Q}{B_S}, \quad (8)$$

where the exergy $B_Q$ of the heat absorbed by the surface $A$ is [3]:

$$B_Q = A\ q\left(1 - \frac{T_0}{T}\right), \quad (9)$$

and the exergy $B_S$ of solar radiation, based on (3), is:

$$B_S = 2.16 \times 10^{-5} A_S\ \varepsilon_{B,S}\ \frac{\sigma}{3}\ (3\ T_S^4 +\ T_0^4 - 4\ T_0\ T_S^3), \quad (10)$$

where the exergetic emissivity of the Sun's surface $\varepsilon_{B,S}$ = 0.426, [4].

The feasibility of the discussed effect of solar radiation concentration can be evaluated by the calculated value of the sum $\Pi$ of entropy increments, which consists of positive (generated) entropy of heat, and emission of surface $A$, as well as negative (disappearing) entropy of absorbed solar radiation:

$$\Pi = \frac{A_S\ q}{a_S T} + \frac{A_S}{a_S}\varepsilon\ \frac{4}{3}\ \sigma\ T^3 - 2.16 \times 10^{-5}\ A_S\ \varepsilon\ \varepsilon_S \frac{4}{3}\ \sigma\ T_S^3. \quad (11)$$

It was assumed that the entropic emissivity $\varepsilon_N$ and $\varepsilon_{N,S}$ corresponding to the surfaces $A$ and $A_S$, is approximately equal to the corresponding energetic emissivity: $\varepsilon_N \approx \varepsilon$ and $\varepsilon_{N,S} \approx \varepsilon_S$, [5].

The sum of entropy increments given by equation (11) should be positive ($\Pi$>0). If this sum is not positive ($\Pi \le 0$), it means that the concentration of solar radiation is impossible because it goes against the second law of thermodynamics.

## 3. Commentary on the Sun's Surface Temperature

In these considerations, a constant and minimum possible temperature of the Sun's surface ($T_S$=7134 K) was assumed. Based on Kondratiev's measurement data on the solar spectrum [6], the solar radiation energy reaching the Earth, also assumed as constant, is calculated [3] as 1367.9 W/m$^2$, which means:

$$1367.9 = 2.16 \times 10^{-5}\ \varepsilon_S\ \sigma\ T_S^4 = const. \quad (12)$$

However, if the temperature $T_S$ turned out to be higher than the minimum value ($T_{S,min}$=7134 K, at $\varepsilon_{S,min}$=0.431), then the emissivity would change according to the relation $\varepsilon_S \times T_S^4$ =

const. This constant can be calculated as follows:

$$\varepsilon_S \ T_S^4 = \varepsilon_{S,min} \ T_{S,min}^4 = 0.431 \times 7134^4 = 1.116 \times 10^{15}. \quad (13)$$

The relation (13) is shown in Figure 2. If the surface temperature $T_S$ of the Sun were higher than the minimum value of 7134 K, then the emissivity $\varepsilon_S$ would fall below 0.431.

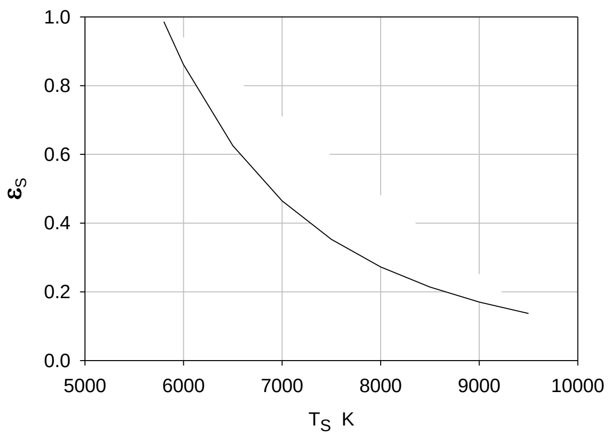


***Figure 2.** Emissivity $\varepsilon_S$ of the Sun's surface as a function of the surface temperature $T_S$ of the Sun.*

# 4. Examples of Using the Model to Analyze the Parameters of the Concentration process

## 4.1. Effect of Concentration Ratio of Radiation

The purpose of these calculations is to show the effect of the variable concentration ratio $a_S$ on the results of extraterrestrial solar radiation concentration. The greater the ratio, the greater the concentration. But there is a question of what happens, for example, with the absorbed heat, its temperature and the efficiency of the concentration process when the ratio $a_S$ increases, and what is the limit of its increase. The calculations use formulas describing the presented model of radiation concentration, assuming an area $A_S$=1 m$^2$ and an ambient temperature $T_0$=300 K.

The left part of Figure 3 shows some concentration effects in the case of relatively mild cooling of the surface $A$, ($q$= 10 W/m$^2$K), and emissivity $\varepsilon$=0.8. As the concentration ratio increases ($a_S$ increases from 1 to 15),

1) the temperature $T$ of the surface $A$ increases monotonically from 395 to 776 K,
2) the absorbed heat $Q$ decreases from 10 to 0.7 W,
3) the exergy $B_Q$ of this heat decreases from 2.4 W to 0.4 W,
4) accordingly to the Q, the energetic efficiency $\eta_E$ decreases from 0.73 to 0.05%,
5) and accordingly to $B_Q$, the exergetic efficiency $\eta_B$ decreases from 0.19 to 0.03%.

For comparison, the right part of Figure 3 shows the effects in the case of the stronger cooling of surface $A$, ($q$=1000 W/m$^2$K) and emissivity $\varepsilon$=0.9. As the concentration ratio increases ($a_S$ increases from 1 to 15),

1) the temperature $T$ of the surface $A$, is higher and increases monotonically now from 450 K to 786 K,
2) the absorbed heat $Q$ is higher but due to the decreasing surface area $A$ decreases from 1000 W to 67 W,
3) accordingly to the Q, the exergy $B_Q$ of this heat decreases from 344 to 42 W,
4) also, accordingly to Q, the energetic efficiency $\eta_E$ decreases from 73.1 to 4.9%, and
5) accordingly to $B_Q$, the exergetic efficiency $\eta_B$, drops from 27 to 3.2%.

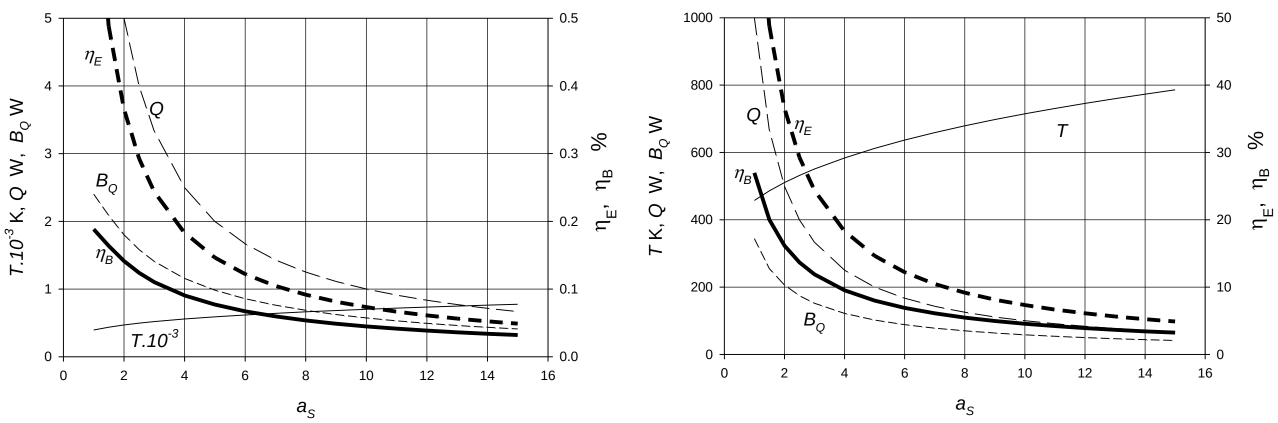


***Figure 3.** Examples of effects of solar radiation concentration, left ($q$=10 W/m$^2$K, $\varepsilon$=0.8) and right ($q$=1000 W/m$^2$K, $\varepsilon$=0.9).*

A comparison of the two diagrams in Figure 3 shows that as the heat rate $q$ increases (from 10 to 1000 W/m$^2$K),

1) the temperature $T$ increases because of greater emissivity $\varepsilon$ of the surface $A$,
2) the total heat $Q$ also increases,
3) and the exergy $B_Q$ of heat $Q$ increases,
4) thus, also the energy efficiency $\eta_E$ increases, and
5) the exergetic efficiency $\eta_B$, increases although it reveals the real estimation of the process and in both cases, it is much lower than the energetic efficiency. In addition, the energy and exergetic efficiency for mild cooling are less than those efficiencies for intensive cooling, respectively, indicating that the considered example of this intensive cooling is more efficient than the considered mild cooling.

In general, the considered comparison shows that the more intense the heat transfer from the surface A, the better the concentration process.

## 4.2. Entropic Approach to the Radiation Concentration Process

As shown in Figure 4, the temperature $T$ of the surface A cannot reach a value higher than the solar radiation temperature of 7134 K. With the increase in the concentration ratio $a_S$, the sum $\Pi$ of entropy increments, calculated by Equation (11), decreases continuously and for the value of 7134 K becomes equal to zero ($\Pi$=0) with a concentration ratio of about $a_S$=107431. A further increase in $a_S$ results in a negative value of the sum of entropy increments, ($\Pi < 0$), which means that it would go against the second law of thermodynamics. For example, the impossible temperature $T$= 7200 K would require a negative value of $\Pi$= -1.876×10$^{-3}$ W/K. Figure 4 shows that as $a_S$ increases, the heat $Q$ decreases, and as calculations show, for the also unreachable theoretical limit case of $\Pi$=0, the total heat rate is only around $Q$=0.9 W, due to the very small surface area $A$.

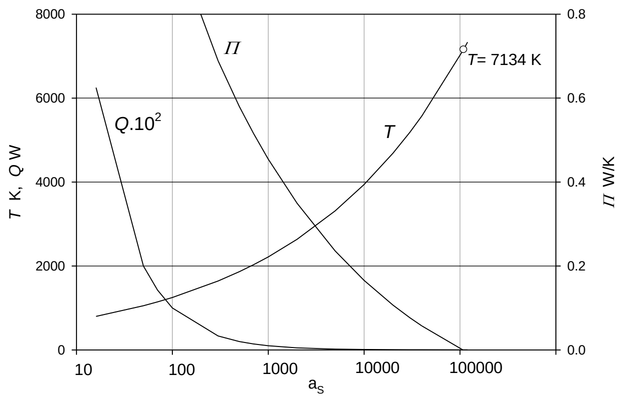


*Figure 4. Limit concentration for solar radiation ($A_S$=1, $\varepsilon$=0.8, $q$=1000 W/m$^2$K, $T_0$=300 K).*

In practice, a certain temperature $T$ is usually required, and the highest possible emissivity value $\varepsilon$ can be arranged by selecting the proper surface material. Therefore, assuming a constant values of temperature $T$ and emissivity $\varepsilon$, Equation (11) can be attempted to be used for optimization to find the minimum sum $\Pi_{min}$ of entropy increments. Equation (11) is treated as a function of ($q$, $a_S$), for which $\Pi_{min}$ would result from the following conditions:

$$\frac{\partial \Pi}{\partial a_S} = -\frac{A_S\ q}{T\ a_S^2} - \frac{4\ A_S\ \varepsilon\ \sigma\ T^3}{3\ a_S^2} = 0 \text{ and } \frac{\partial \Pi}{\partial q} = \frac{A_S}{a_S T} = 0, \quad (14)$$

which, (q = - 4 ε σ $T^4$/3, and $A_S$=0) do not indicate the existence of an optimal value of $\Pi_{min}$. In such a situation, the concentration process could, for example, be designed by assuming the temperature $T$, using an absorbing surface with a given emissivity $\varepsilon$, and then, by varying the heat transfer intensity ($q$), determine the acceptable concentration ratio $a_S$ and other process parameters, such as total heat or efficiency.

## 4.3. Energy and Exergy Balances of Radiation Concentration Process

Radiation concentration is a process that can be the subject of thermodynamic analysis [2] using the first and second laws of thermodynamics. This analysis is based on the equations of conservation of energy and exergy. In general, the developing of an energy and exergy balances allows for a better understanding of the process, facilitates its design and control, determines the degree of perfectness and the need for process improvement and optimization, and thus also allows for process motivation. To perform thermodynamic analysis, it is required to define the system under consideration. For the process of radiation concentration, such a system can be a radiating-absorbing surface, which is surface $A$ in Figure 1. This system is therefore an infinitely thin layer into which energy and exergy are only delivered or carried out. The energy balance of such a system was expressed by Equation (5):

$$2.16 \times 10^{-5}\ A_S\ \varepsilon_S\ \sigma\ T_S^4 = 2.16 \times 10^{-5}\ A_S(1-\varepsilon)\ \varepsilon_S\ \sigma\ T_S^4 + A\ \varepsilon\ \sigma\ T^4 + A\ q. \quad (15)$$

Equation (5) shows the radiant energy delivered to the surface $A$ (the left side of this Equation) as equal to the terms on the right side of this Equation, which are the energy reflected from surface $A$, the energy emitted by that surface and the heat transferred from that surface.

The equation of the exergy balance is analogous to the equation of energy (5), except that on the right side it contains an additional term representing the irreversibility of the phenomenon of concentration, which is determined as the product of the sum $\Pi$ of entropy increments (Equation 13), and the ambient temperature:

$$2.16\times10^{-5}\ A_S\ \varepsilon_{B,S}\ \frac{\sigma}{3}\ (3\ T_S^4+\ T_0^4-4\ T_0\ T_S^3)=$$

$$2.16\times10^{-5}\ (1-\varepsilon_B)\ A_S\ \varepsilon_{B,S}\ \frac{\sigma}{3}\ (3\ T_S^4+\ T_0^4-4\ T_0\ T_S^3)+\ A\ \varepsilon_B\ \frac{\sigma}{3}(3\ T^4+\ T_0^4-4\ T_0\ T^3)+A\ q\ \left(1-\frac{T_0}{T}\right)+\ \Pi\ T_0.\ (16)$$

It has been assumed that the exergetic emissivity $\varepsilon_B$ of surface $A$ is approximately equal to the energetic emissivity of this surface, $\varepsilon_B \approx \varepsilon$, [5].

Equations (5) and (16) can be illustrated using a band diagram (Sankey diagram). Figure 5 shows the energy balance (part a) and the exergy balance (part b) in the case of mild cooling (left part of Figure 3). For both diagrams, the situation was chosen at $a_S$ = 3 and $\varepsilon$=0.8, in which the surface A has temperature $T$= 494 K. Solar radiation energy of 1367 W, (100%), is delivered to the system, from which the reflected radiation energy of 20%, the emitted radiation energy of 65.8%, and the usable heat of 14.2%, equal to the energetic efficiency, are carried out.

Part b of Figure 5 shows the solar radiation exergy of 1275 W, (100%), delivered to the system, from which reflected radiation exergy 20%, the emitted radiation exergy 16.6%, and usable heat exergy 6.0%, equal to exergetic efficiency, are carried out. The balance closes with an exergy loss of 57.4% due to the irreversibility of the process. It should be noted that energy consideration does not reveal any losses. Only an exergetic analysis reveals the degradation of solar energy.

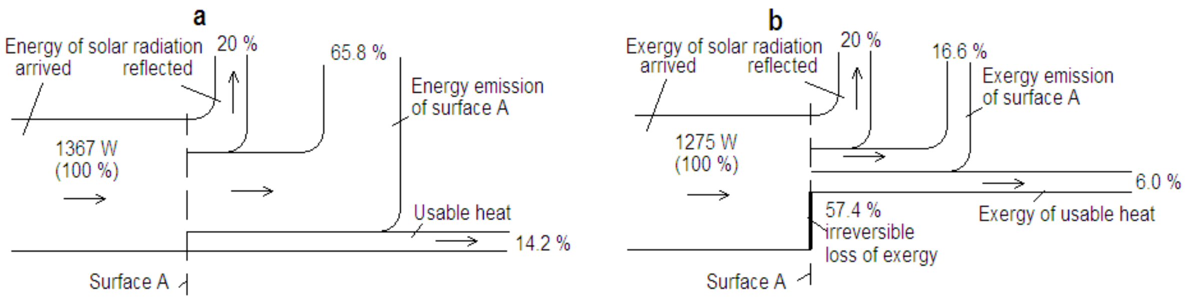


***Figure 5.*** *Band diagrams for mild cooling, ($a_S$= 3, q=582 W/m²K, T=494 K).*

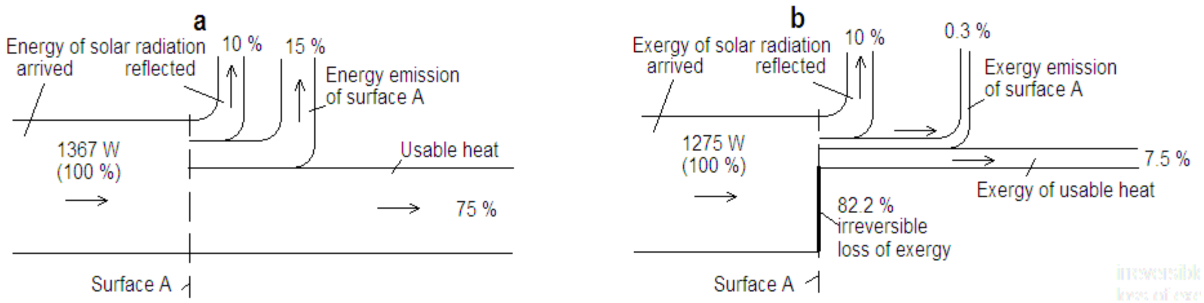


***Figure 6.*** *Band diagrams for intensive cooling, ($a_S$=3, q=3100 W/m²K, T=331 K).*

Figure 6, analogous to Figure 5, shows the energy balance (part a) and the exergy balance (part b) for the case of intensive cooling (right part of Figure 3). For both diagrams, the situation at $a_S$= 3 and $\varepsilon$=0.9 was chosen, in which the temperature of surface $A$ is $T$= 331 K. The system is delivered with solar radiation energy of 1367 W, (100%), and the reflected radiation energy of 10%, the energy of emitted radiation of 15%, and the usable heat of 75%, equal to the energetic efficiency, are carried out.

Part b of Figure 6 shows the exergy of solar radiation of 1275 W, (100%), delivered to the system, from which the exergy of reflected radiation 10%, the exergy of the emitted radiation 0.3%, and the exergy of usable heat 7.5%, equal to the exergetic efficiency, are carried out. The balance equation closes with an exergy loss of 82.2% due to the irreversibility of the concentration process. This loss is greater compared to the previous case (Figure 5), due to the greater degradation of solar radiation, (to a lower temperature 331 K).

The diagrams shown in the two Figures 5 and 6 compare two very different concentration processes, in which the concentration ratio is the same, $a_S$=3, but the heat received from the surface $A$ is different. Different heat transfer intensities were used in these processes. In the first one, the heat transfer was mild, $q$=582 W/m$^2$K, and in the second one, intensive heat transfer was used, $q$=3100 W/m$^2$K. On all diagrams the energy and exergy of the incoming solar radiation do not differ much, and the exergy-to-energy ratio for the surface temperature of the Sun, $T_S$=7134 K, is 1275/1367= 0.9329. The emission of energy (in W) from the Sun is correspondently greater than the emission of exergy. On the diagrams, these values are assumed to be 100%.

The reflected solar energy is 20 and 10% respectively in Figures 5 and 6, as is the reflected exergy in these Figures. This is due to the correspondently different emissivity of surface $A$, ($\varepsilon$=0.8 and $\varepsilon$=0.9). The energy emission from surface $A$ is always greater than the exergy emitted.

The emitted energy in Figure 5 is relatively high and amounts to 65.8%, due to the temperature of this surface, $T$=494 K, but the exergy of this emission at such a temperature is only 16.6%. The usable heat is relatively low (14. 2%), due to the mild cooling of the surface $A$, ($q$=582 W/m$^2$K), and exergy of this heat is lower (6%), as is equal to this heat multiplied by the Carnot factor, (1-$T_0$/$T$). Process perfectness (Figure 5) is estimated by the value of exergy loss, (57.4%). Displaying such irreversibility of the process is an advantage of exergetic analysis. The energy diagram does not reveal any energy loss, because the energy has no ability of displaying the degradation of energy.

Figure 6 shows the diagrams of the concentration process at a lower temperature of surface $A$, ($T$=331 K). However, despite the higher energetic emissivity ($\varepsilon$=0.9) of surface $A$, the energy emission is lower (15%) and the emission of exergy, (0.3%), is correspondently smaller. Intensive heat transfer ($q$=3100 W/m$^2$) results in a large amount of usable heat, (75%), the practical value of which, however, measured by exergy, is only 7.5%. Obviously, there is no loss of energy, while the exergy balance shows a relatively very large loss of exergy (82.2%) due to the irreversibility of the process caused by the significant degradation of solar radiation from temperature 7134 to 431 K and due to intensive heat transfer.

The portion of solar radiation reflected from surface A has an unchanged spectrum and temperature, and therefore this reflection is a reversible phenomenon that does not cause exergy losses. For the same reason all the reflections from cone surface of the model in Figure 1, are reversible, not changing solar radiation arriving finally in surface A.

Thus, the irreversibility of the concentration process occurs only due to the other two phenomena. The first, is the absorption of solar radiation into the heat $Q$' transferred from surface A, and the second, is the change of the heat Q" into the emission of surface A. The effective heat $Q$= $Q$'- $Q$" is used in the energy balance Equation (5), ($Q$=$A$ $q$). Based on the law of energy conservation, heat $Q$' is equal to the energy of absorbed solar radiation, and heat $Q$" is equal to the energy emitted. The values of each of exergy loss (in W) due to irreversibility is calculated by multiplying of the respective increase of entropy by the ambient temperature $T_0$. The respective entropy increments are determined based on the terms of the right side of Equation (11). Exergy loss $\delta B'$ due to absorption:

$$\delta B' = \left(\frac{2.16\times10^{-5} A_S\ \varepsilon\ \varepsilon_S\ \sigma\ T_S^4}{T} - 2.16\times10^{-5}\ A_S\ \varepsilon\ \varepsilon_S \frac{4}{3}\ \sigma\ T_S^3\right) T_0 = 2.16\times10^{-5} A_S\ \varepsilon\ \varepsilon_S\ \sigma\ T_S^3 \left(\frac{T_S}{T} - \frac{4}{3}\right)\ T_0, \quad (17)$$

and exergy loss $\delta B''$ due to emission on surface $A$:

$$\delta B_R = \left(A\ \varepsilon\ \frac{4}{3}\ \sigma\ T^3 - \frac{A\ \varepsilon\ \sigma\ T^4}{T}\right) T_0 = \frac{1}{3} A\varepsilon\sigma T^3 T_0. \quad (18)$$

For example, in the case of mild cooling ($q$=582 W/m$^2$K), Equation (17) yields $\delta B' \approx 603$ W, (44.3%), and Equation (18) yields $\delta B'' \approx 182$ W, (13.1%). Similarly, in the case of intensive cooling ($q$=3100 W/m$^2$K), $\delta B' \approx 1000$ W, (78.1%), and $\delta B'' \approx 55$ W, (4.1%), are obtained. The main irreversibility in the radiation concentration process is due to adsorption of solar radiation and the greater the irreversibility, the lower the temperature $T$ of the heated surface A.

## 4.4. Optimal Temperature of the Heated Surface

The introduced mathematical model of radiation concentration can be used in various ways. Figures 5 and 6, using the band diagrams, show energy and exergy balances of the concentration process for the assumed two values of temperature $T$ (494 and 331 K) of heated surface $A$. However, for example, the items of band diagrams can be shown over a wide range as a function of this temperature $T$. Figure 7 shows the balance items for temperature $T$ in the range of 400 to 800 K, assuming $\varepsilon$=0.95, $a_S$=20 and $T_0$=300. As shown in Figure 7, only the exergetic balances disclose a certain optimal temperature $T_{opt}$. The calculation of this optimal temperature can be based on Equation (8) for exergetic efficiency, in which $B_Q$ is determined by Equation (9), $B_S$ is determined by Equation (10) and $Q$ is expressed from the energy balance Equation (5). Then the condition for the occurrence of the optimum is:

$$\frac{d\eta_B}{dT} = -4\frac{A\ \varepsilon\ \sigma}{B_S}\ T_{opt}^3 + \frac{\varepsilon\ T_0}{T_{opt}^2} + 3\frac{A\ \varepsilon\ \sigma\ T_0}{B_S}\ T_{opt}^2 = 0, \quad (19)$$

of which $T_{opt}$= 562.3 K.

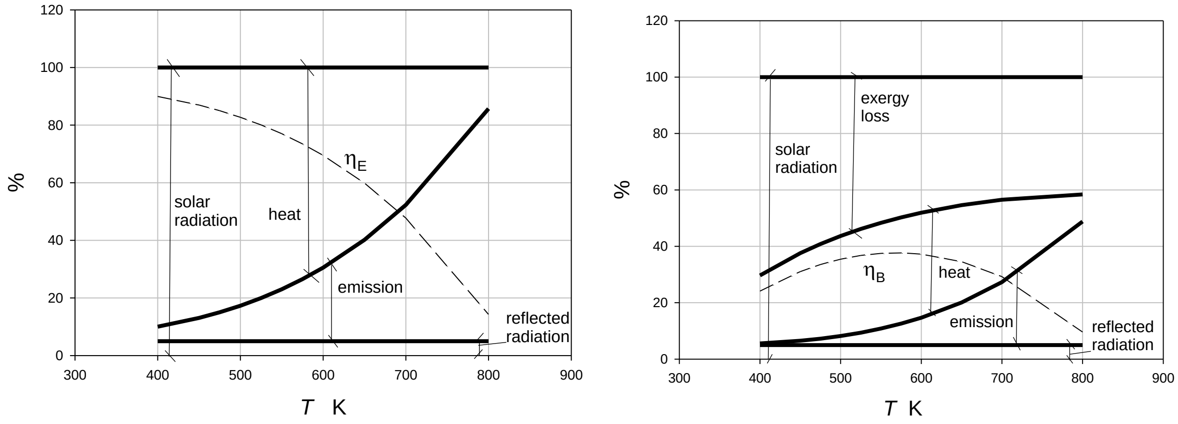


***Figure 7.*** *Energetic balances (left) and exergetic balances (right) of the heated surface A.*

As can be seen in Figure 7 (left), as the temperature $T$ of surface $A$ increases, the exergy emission of this surface increases, which reduces the heat absorbed by this surface and hence the energetic efficiency $\eta_E$ decreases monotonically. High energetic efficiency $\eta_E$= 90%, for $T$=400 K, decreases with increasing temperature $T$ and reaches 14.3% for $T$= 800 K.

Figure 7 (right) shows an exergetic interpretation of the concentration process and, above all, its significant imperfectness, manifested by a relatively large loss of exergy, which however, decreases with the increase in temperature $T$. Compared to the energetic point of view, the exergy of emission is of lesser importance, and the practical value of the absorbed heat, expressed by the exergy value of this heat, reveals a maximum corresponding to the optimum exergetic efficiency $\eta_{B,opt}$= 37.7%, (for $T$= 575 K).

## 4.5. Effect of the Emissivity on the Heated Surface

Another example of the application of the presented model may be the determination of the effect of the emissivity $\varepsilon$ of the heated surface A on the efficiency of the radiation concentration process. The results of the calculations are shown in Figure 8.

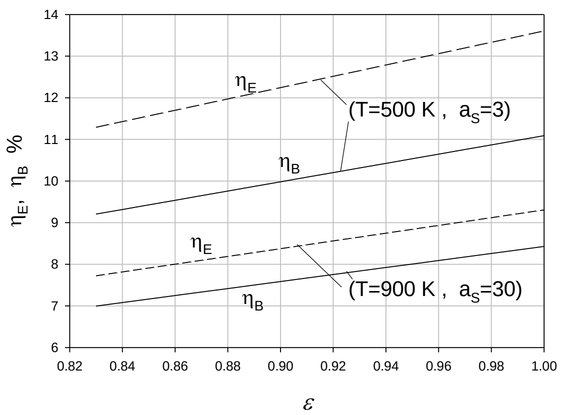


***Figure 8.*** *Example of the effect of emissivity $\varepsilon$ on energetic efficiency $\eta_E$ and exergetic efficiency $\eta_B$.*

Both energetic and exergetic efficiency increase with the increase in emissivity $\varepsilon$ of surface $A$. However, these efficiencies decrease with an increase in the required temperature $T$, and an increase in this temperature $T$ requires an increase in the concentration ratio $a_S$.

## 4.6. Effect of Ambient Temperature

The presented model can also be used to determine the influence of the ambient temperature $T_0$ on the radiation concentration process.

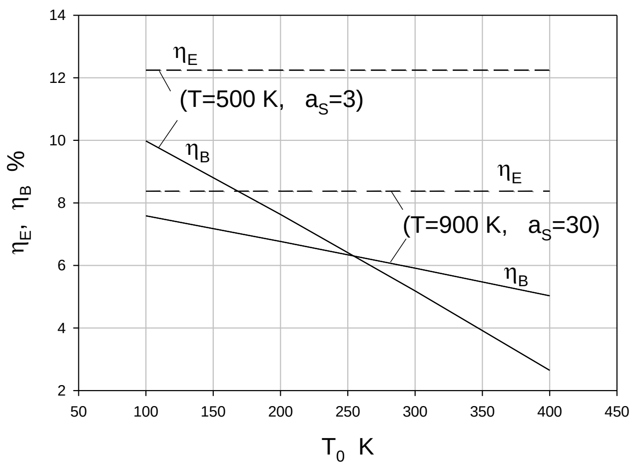


***Figure 9.*** *Example of the influence of ambient temperature $T_0$ on energetic efficiency $\eta_E$ and exergetic efficiency $\eta_B$, ($\varepsilon$=0.9).*

Geographical location, weather or season have an impact on the ambient temperature $T_0$. Based on the calculations, Figure 9 shows an example of the influence of the ambient temperature $T_0$ on the energetic efficiency $\eta_E$ and exergetic $\eta_B$ efficiency, when the emissivity of the surface $A$ is equal to $\varepsilon$=0.9. Energetic efficiency is insensitive to ambient temperature. However, the exergetic efficiency is the greater the lower is the ambient temperature, and theoretically for $T_0$=0 it would be equal to the energetic efficiency, because the exergy radiation at such a temperature is equal to energy.

### 4.7. Temperature of the Heated Surface

The most important goal of the process of concentration of solar radiation seems to be to obtain the required value of temperature *T* of the heated surface *A*. The presented model allows to determine this temperature as a function of the concentration ratio $a_S$ and heat rate *q*, as shown in Figure 10. To obtain the required temperature *T*, a certain minimum concentration ratio of $a_S$ is required, and then the total heat *Q* is produced in proportion to the applied heat rate *q*.

For example, if a temperature of *T*=1000 K is needed, then using the concentration ratio $a_S$ = 44, a heat rate of *q*=3112 W/m$^2$ is required to obtain the total heat $Q = q/a_S$ = 3112/44 = 70.7 W. This means that solar radiation arriving within a cross-section area of 1 m$^2$, concentrated on the irradiated surface with an area of *A*=1/44= 0.0227 m$^2$, allows the generation of heat *Q*= 70.7 W.

However, to obtain the same temperature *T*= 1000 K, one can use, for example, the concentration ratio $a_S$= 56, and then from the area of *A* = 1/56 = 0.0179 m$^2$, at *q* = 17877 W/m$^2$, obtain the heat *Q*= 17877/56 = 319 W.

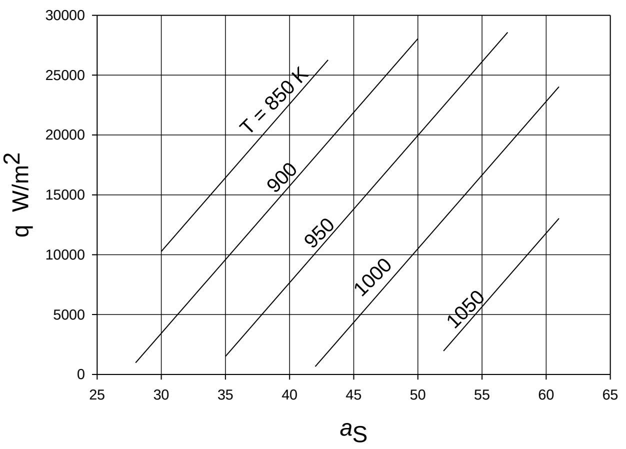


***Figure 10.*** *The temperature T of the heated surface A, (ε=0.9), as a function of concentration ratio $a_S$ and heat rate q.*

The diagram in Figure 10, can also be used to determine the required concentration ratio $a_S$ for a given value of *q* to obtain the required temperature *T*. Another possibility of using the diagram is to predict the temperature *T* for the given values of $a_S$ and *q*.

## 5. Remarks on the Concentration of Solar Radiation at the Earth Surface

The World Metrological Organization promotes a value of 1367 W/m$^2$ for the irradiance of the Sun on the outer atmosphere. Solar radiation passing through the atmosphere, is weakened by absorption and scattering processes due to the presence of gas molecules, water and dust. Determining the intensity of solar radiation reaching the Earth's surface requires complex calculations. Such calculations and observations indicate that globally about 30% of solar radiation reaching the Earth is reflected from the atmosphere, 20% is absorbed by it, and only 50% of energy reaches the Earth's surface. These values can vary significantly locally. The total solar radiation on a horizontal surface of the Earth consists of a direct radiation and diffuse radiation. For a typical cloudless atmosphere in summer, the amount of 1367 W/m$^2$ reaching the outer atmosphere, is on the Earth surface reduced to around 1050 W/m$^2$ direct beam radiation with additional around 70 W/m$^2$ of diffuse radiation also reaching the horizontal surface at ground level, [17].

The model shown in Figure 1 cannot be applied for determining the actual radiation reaching the Earth's surface. However, with the help of this model, it is possible to carry out indicative considerations to, for example, approximately evaluate the process of concentration of only direct solar radiation reaching the Earth surface in the amount of 1050 W/m$^2$. For this purpose, in Equation (5), the following assumption can be made:

$$2.16 \times 10^{-5} A_S \ \varepsilon_S \ \sigma \ T_S^4 = 1050. \tag{20}$$

It is worth noting that the considerations on entropy could only be carried out if the spectrum of the radiation under consideration was known [4].

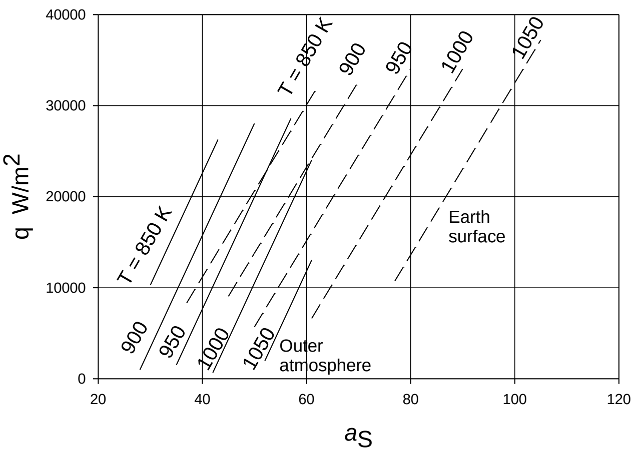


***Figure 11.*** *Comparison of the obtained temperature T of the heated surface A, (ε=0.9), in the process of concentration of extraterrestrial radiation (solid lines) and radiation of 1050 W/m$^2$ on the Earth's surface (dashed lines).*

Taking into account Equation (20) in Equation (5), it is possible to calculate, for example, the temperature *T* of a heated surface *A* located on the Earth's surface and irradiated by direct solar radiation. The results of such calculations are shown in Figure 11 (dashed lines). For comparison, Figure 11 also shows the temperature values $T$ (solid lines) determined for extraterrestrial radiation (Figure 10). As can be seen from the comparison, weakened radiation reaching the Earth's surface requires a higher concentration ratio $a_S$. For example, with extraterrestrial radiation (1376 $W/m^2$) the temperature $T$=1000 K can be generated at $q$=20000 $W/m^2$ and concentration ratio $a_S$=57.3, while with the use of radiation of 1050 $W/m^2$ the same temperature of 1000 K and at the same heat rate $q$=20000 $W/m^2$, can be achieved with a higher concentration ratio of $a_S$=75.1.

## 6. Conclusions

Solar radiation has a high temperature, but it is highly diluted. The use of such radiation is relatively inefficient. One of the ways to use solar radiation is its optical concentration. Extraterrestrial solar radiation reaching the Earth's atmosphere has a specific spectrum for which the temperature and emissivity of the Sun's surface can be assumed. Solar radiation on the Earth's surface is significantly attenuated because as it passes through the atmosphere layer, the spectrum, the solid angle of radiation propagation changes, and the radiation energy varies depending on the season, day, and geographical location. For example, when the Sun is at its zenith, solar radiation passes through a layer of atmosphere about 40 km thick that surrounds the Earth about 12000 km in diameter. However, horizontally, solar radiation would pass through an atmosphere about $(6040^2\text{-}6000^2)^{1/2}$=694 km. The process of concentrating solar radiation on the Earth's surface is complex, and a strict mathematical description of this process is difficult.

The presented considerations concern extraterrestrial solar radiation, for which the temperature and emissivity of the Sun's surface are known. The results of considerations on such radiation may have direct application for concentrating devices located above the Earth's atmosphere, where at most only the solid angle of the only incoming radiation can change.

However, for the location on Earth, the presented considerations also have some value, because they allow us to estimate, qualitatively and approximately quantitatively, the trends of the output data in response to changes in the input parameters of the solar radiation concentration process. These tendencies are discussed and explained based on the laws of thermodynamics.

The presented paper shows examples of various analyses of the process of extraterrestrial radiation concentration, based on the original mathematical model of this process. The results obtained can provide a guide for designers of heat exchangers irradiated by concentrated solar radiation.

The presented considerations already introduce new values of solar surface temperature and emissivity [4]. Based on entropy considerations, a new limit (7134 K) of concentration temperature was also indicated. The developed thermodynamic analysis of the concentrating process in accordance with the introduced mathematical model shows the relationships between the main parameters of the process, such as concentration ratio, absorbing surface temperature and emissivity, absorbed heat, ambient temperature and energetic and exergetic efficiency of the process. The exergetic balance of the heat-absorbing surface was used to identify exergy losses caused by irreversible absorption of solar radiation and irreversible energy emission by the heated surface. A large predominance of the value of irreversibility of absorption over irreversibility of emission was found.

This work is a contribution to the thermodynamic discussion for a better understanding of the process of solar radiation concentration. It can be assumed that the cognitive and innovative approach to the concentration of solar radiation considered in this work has the potential to inspire researchers and scientists. Among the many possible directions for further research development is, for example, the analysis of the possibility of applying the issues raised in the article to the fields in which the source of heat at the desired temperature is concentrated solar radiation.

## Author Contributions

Ryszard Petela is the sole author. The author read and approved the final manuscript.

## Conflicts of Interest

The author declares no conflicts of interest.

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## Research Fields

**Ryszard Petela:** Thermodynamic analysis of energy processes, Theory of exergy, Radiation exergy, Heat transfer, Theory of solid gasification, Atomization of liquids, Fuel technology and combustion, Coal agglomeration, Flame noise