

EXERGY OF SOLAR RADIATION

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Summary

Solar radiation is the most important source of renewable energy. This radiation is considered a thermal type, which means that it is emitted by the body if its absolute (thermodynamic) temperature is greater than zero. For the purpose of use, this radiation is estimated by its energy, and additionally by exergy, which is a more effective criterion of it for determining working capacity. Radiation of the body is the process of transferring energy by emitting photons, which are indivisible quanta of energy. The properties of a photon population trapped in an enclosed space are discussed like photon gas to determine its exergy. The other exergy formula is derived for radiation emitted from a surface at a known temperature. However, in practice, radiation is a combination of emissions from surfaces with different temperatures, and in addition can be significantly transformed during propagation in atmospheric air. The solar radiation reaching the earth's surface is just an example of such arbitrary radiation. Therefore, a methodology is proposed for calculating the exergy of all kinds of radiation. The derived exergy formulae take into account that the solid angle in which the radiation propagates and its energy spectrum are determined by measurements. The differential expressions in theoretical formulae are replaced by the finite differences. Exergy of extraterrestrial solar radiation was calculated in a simple and more accurate way using the proposed methodology. It was shown that the energy flux density of extraterrestrial solar radiation is 1371W/m^2 , while the exergy flux density of this radiation is 1282W/m^2 , which is 0.93 fraction of its energy. In conclusion, some typical applications of the derived exergy formulae for solar radiation are outlined.

1. Significance of Exergy

Nature appears to us as a system of matter and energy in interplay. We humans understood that the matter is either a substance that you can touch, or the effect of a field that you can sense and we noticed the effects of many different fields on substance. Gravity and electromagnetic waves are examples of fields, and electromagnetic waves are radiation of heat. Both kinds of matter are in continuous action, driven by energy and its changing form.

Thermodynamics has evolved, as the science of matter and energy and their transformation. To facilitate thermodynamic considerations, parameters such as temperature, pressure, density were used to describe the state of matter at any time. In order to further facilitate the considerations, other concepts describing the state of matter have been introduced. They were called function of the state of matter, which, using the parameters of the state matter, describe matter from different points of view. For example, a state function called energy defines the ability to do work. Keep in mind that heat and work are not energy, but just ways to transfer energy – thermally (by conduction, convection, and radiation) and mechanically respectively. Heat and work are only transfer phenomena that can last for a limited period of time, sometimes for a very long time, e.g. solar radiation.

Using this concept of energy, the observation of nature is described. For example, the most important observation is that the energy delivered somewhere is equal to the energy taken from there, although most often in a changed form. But energy (E) never disappears:

$$E = \text{const.} \quad (1)$$

This quantitative energy feature was a valuable basic information in the development of human progress in various sciences and technologies. For practical reasons, other state functions have also been defined in order to conveniently organize the energy analyses of different thermodynamic systems. For example, energy may be expressed in particular by *enthalpy*, which is defined to determine the energy of a substance when a substance enters or leaves any system under analysis. Enthalpy takes into account the transport work performed by the substance during the exchange with the system. The energy of a substance that remains in the system under consideration is expressed using a state function called *internal energy* (Burghardt, 1982).

Another observation of nature was that the processes proceed spontaneously only along the direction of decrease of the driving parameters. Heat flows towards lower temperature and fluids flow towards lower pressure. Friction causes a drop in fluid pressure. Spontaneous processes occur in which matter participating in it, achieves a more common state - lower temperature, lower pressure, which means a state of greater thermodynamic probability. In other words, the greater the ability of matter (a sense of orderliness) to initiate any process, the less probable such a state of matter. Therefore, the state function, called *entropy*, is defined to express the thermodynamic probability of the state of matter. It is a measure of disorder. Using entropy, nature observation can be expressed by a law that says that processes proceed in such a way that the overall

algebraic sum (Π) of entropy changes of all matters involved in the process, is always nonnegative:

$$\Pi \geq 0 . \quad (2)$$

That is, the disorder in a system always increases in a real process. Π is zero for the ideal process and positive is for real processes. Heat transfer along the decreasing temperature cannot be reversed, and also you cannot reverse the flow of a fluid to regain pressure. These are examples of irreversible processes. Heat transfer is irreversible due to the finite temperature difference that drives the transfer. Reversible heat transfer would only take place in the absence of a temperature drop, which means a very slow process, and the entropy of the transferred heat would then remain unchanged. Otherwise, a drop in temperature causes an increase in the entropy of the heat. Similar to heat flow, the entropy of a flowing fluid increases due to friction. Friction is converted into heat, which is partially absorbed by the fluid and can be partially released into the surroundings. The less probable the state of matter, the less its entropy is. Therefore, in nature, everything moves towards a greater probability of the situation, that is, it tends to make a larger sum of entropy changes. Entropy allowed us to understand the essence of irreversibility and improve processes.

Use entropy in the determination of the quantitative effect of irreversibility was a great discovery. The consequence of irreversibility is the loss of possible work. According to the Gouy-Stodola theorem, the overall increase in entropy is used to calculate the related loss (δW) due to irreversibility:

$$\delta W = \Pi T_0 , \quad (3)$$

where (T_0) is the temperature of the environment. The loss δW is unavoidable and unrecoverable. The discovery of the law expressed by Eq. (3) therefore inspired the definition of an additional function of the state of matter, called *exergy*. In contrast to energy, which is basically defined as ability to work, exergy is also the ability to work, but in the human environment, because the environment is the only reference level for practical estimation of matter. An environment is defined by its temperature and pressure when physical processes are considered. However, the environment is also a reference level for chemical processes as it consists of worthless reference substances in a state of equilibrium with the environment. Substances in the environment that are not in a stable equilibrium with it are valuable and called energy resources. Pure carbon (C) can be an example of valuable substances and common carbon dioxide (CO₂) is an example of environmental equilibrium reference for determining the chemical value of carbon. The environment is also a source of worthless heat and radiation at the level of temperature T_0 .

Therefore, the *exergy of any matter is defined as the maximum work that this matter can do during the reversible process of bringing matter into equilibrium with natural environment without changing other matters, except only quantitative changes in the environment*. On the basis of this definition, the following formula was obtained for exergy (B) of the substance *entering or leaving* the system concerned:

$$B = H - H_0 - T_0(S - S_0), \quad (4)$$

where:

- H : Enthalpy of the substance under consideration at any state (T, p),
 H_0 : Enthalpy of that substance at environment temperature (T_0) and at concentration or partial pressure (p_0) in equilibrium with the environment,
 S : Entropy of the substance under consideration in (T, p),
 S_0 : Entropy of the same substance at equilibrium with the environment at (T_0, p_0).

Analogous to internal energy, exergy (B_U) of a substance of volume (V) and at pressure (p) always *inside the system*, can be defined as:

$$B_U = B - V(p - p_0), \quad (5)$$

where (p_0) is the pressure in the environment and (B) is exergy of the same substance, but when it crosses the system boundary.

The concept of energy is commonly used in the analysis of problems and processes. However, sometimes this leads to confusing results. Using energy, it is impossible to distinguish the quality of 1 J (Joule) of heat, 1 J of work or 1 J of electricity, while both work and electricity are practically more valuable than heat. The practical value of 1 J of heat at 30°C is significantly less than 1 J of heat at 600°C. The impossible spontaneous transfer of heat from cold to hot source is not questioned from the point of view of energy conservation. There are more other examples of such energy defects.

The concept of exergy is a bit more difficult to apply to problem and process analysis. However, exergy eliminates the disadvantages of the energy concept. Exergy determines the practical value of matter, and the work is chosen as a criterion of measure, because work is a possible transfer of energy at an unlimited temperature level. Energy analysis is a key approach to investigating problems or processes, but additional exergy analysis allows for qualitative evaluation and additional interpretation of the subjects studied, (Szargut and Petela, 1965), (Szargut et al, 1988).

Initially, exergy was applied to thermodynamic consideration of substances and heat, but only since 1960, exergy was applied to thermal radiation. (Petela, 1960). Radiation exergy has become the subject of a wide debate in literature, to which many authors have brought different approaches based on classical or statistical thermodynamics, (Badescu, 2008). However, the accuracy of the radiation exergy formulae presented below has been confirmed.

2. Photon gas

One of the main phenomena appearing in the surrounding nature is radiation. It should be noted that radiation has two meanings; it can be a radiating process of the body or it can be a product of this process. Four types of radiation are possible; alpha, beta,

neutron, thermal, and only the last is considered here. Thermal radiation is due only to the temperature of the radiating body. During the process of radiation of the body (which may be solid, liquid or some gases), part of its energy, (like internal energy or enthalpy), is converted into the energy of spreading electromagnetic waves. Radiation does not need a medium in which to spread. Electromagnetic waves propagate even in vacuum. From a different point of view, energy radiates from the body in a pulsating way, and each pulse is emitted in the form of the smallest indivisible quanta of energy, called photons.

For a large population of photons, some thermodynamic parameters are applied similar to those used for a large population of substance molecules. Photon populations can appear either as photons trapped in a system with limited space or as a stream of photons moving through space. Situations of trapped or traveling photons are similar to the states of substance expressed by internal energy or enthalpy, respectively. Trapped photons are analyzed in this Section, the moving stream is the subject of the following Sections.

The concept of *temperature* in radiation problems can only be applied to a batch of photons, and the temperature (T) of thermal radiation can then be determined indirectly, that is, by measuring the temperature of the substance of which the radiation is in the thermodynamic equilibrium, (Bejan, 1997).

The *internal energy* (U), in J (Joule), of photon gas in space volume (V), at thermodynamic temperature T , is:

$$U = a V T^4 . \quad (6)$$

where (a) is the universal constant. Rest mass of photon gas is zero, so energy U cannot be related to the mass of that gas but rather to its volume. Thus, the energy density u , J/m³, of photon gas, is:

$$u = \frac{U}{V} = a T^4 . \quad (7)$$

Entropy (S) of photons in the space of volume V , is determined as:

$$S = (4/3)a V T^3 . \quad (8)$$

Radiation carries linear momentum and exerts radiation *pressure* on the irradiated object. This pressure also occurs in the internal structure of radiation and the application of a theorem with an equal energy distribution in three-dimensional space, allows us to express the pressure (p) of photons as:

$$p = u / 3 . \quad (9)$$

or using Eq. (7) in (9):

$$p = (a/3)T^4. \quad (10)$$

One of the possible processes of photon gas of volume V is a frictionless and *adiabatic process*, that is, during which photon gas does not exchange heat with the surrounding. Thus, the entropy of processed photon gas remains constant and Eq. (8) for this gas may be written as:

$$VT^3 = \text{const.} \quad (11)$$

Equation (11) means that during the process the volume V and the temperature T may change but they do in such a way that Eq. (11) is always fulfilled. The elimination of the temperature T in Eq. (11) by the pressure p using the formula (10) gives:

$$pV^{(4/3)} = \text{const.} \quad (12)$$

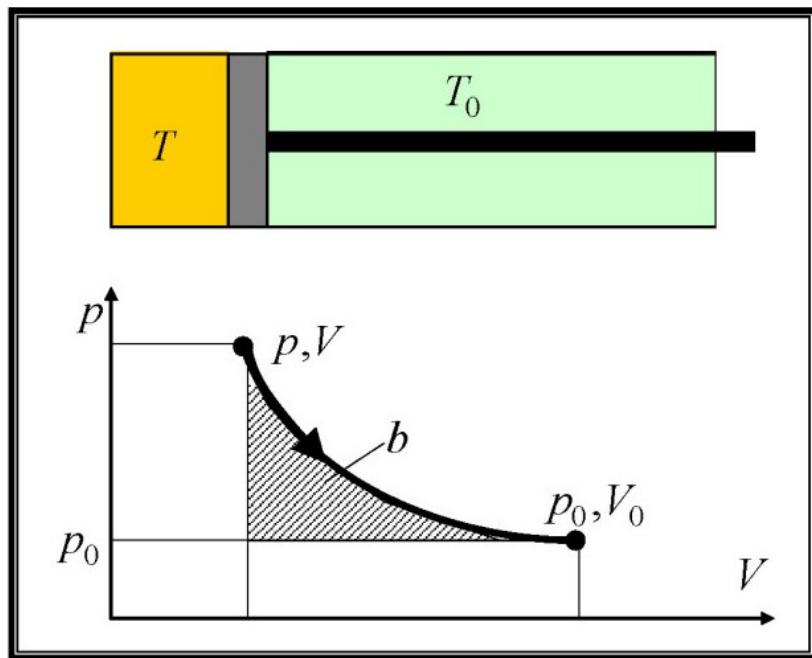


Figure 1. Photon gas in cylinder with piston

Photon gas *exergy* must express the maximum ability to perform work under the conditions determined by the environment. In order to determine this work, the model of the cylinder with piston, placed in a vacuum, may be analyzed, (Figure 1). Initially, the cylinder is filled with photon gas of volume V , at thermodynamic temperature T and pressure p . Cylinder walls and piston base are perfectly reflective like mirrors, ensuring no heat exchange between the gas and the walls. The space on the other side of the piston is filled with environmental radiation at absolute environment temperature T_0 . According to Eq. (10), the higher the temperature, the higher the photon gas pressure. Due to the temperature difference, the piston can move to the right if $T > T_0$, or to the left if $T < T_0$. Thus, the first observation is that the photon gas at $T \neq T_0$ is

always able to do the work by moving the piston, and thus, has an exergy value greater than zero. Then, consider the exergy value. When the pressure p changes to achieve p_0 , the volume V also changes. The elemental work dW occurs with an elemental volume change dV and at an instant pressure p , so $dW = p \cdot dV$. The total work W performed in the model may be calculated as following:

$$W = \int p dV. \quad (13)$$

However, exergy (b) of photon gas is equal to the work performed until the gas in the considered process approaches the environment temperature, $T \rightarrow T_0$, and the corresponding values of pressure, $p \rightarrow p_0$, and volume, $V \rightarrow V_0$. The process is represented by a bold curve in the diagram (Figure 1). The total work W done by the gas during expansion to pressure p_0 is represented by the area between the curve and the axis of coordinate V . However, in order to calculate the useful work (exergy), the part $p_0(V_0 - V)$ performed on the “compressing” of the environment must be subtracted from W :

$$b = \int_V^{V_0} p dV - p_0(V_0 - V). \quad (14)$$

The shadowed area in the diagram (p, V) in Figure 1 represents the exergy (b) of the photon gas under consideration. The integral in Eq. (14) is solved after substitution obtained from Eq. (12):

$$p = \frac{p_0 V_0^{(4/3)}}{V^{(4/3)}}. \quad (14a)$$

Equation (14) takes the form:

$$b = p_0 \left(3V_0^{(4/3)}V^{-(1/3)} - 4V_0 + V \right). \quad (14b)$$

Then, assume in Eq. (14b) the initial volume of photon gas $V = 1\text{m}^3$, eliminate V_0 with Eq. (14a), and eliminate pressures p and p_0 using Eq. (10). The final formula is obtained as:

$$b = \frac{a}{3} \left(3T^4 + T_0^4 - 4T_0 T^3 \right). \quad (15)$$

The photon gas exergy at a relatively low temperature T , in an environment at temperature T_0 , is presented in Figure 2. Except when $T = T_0$, exergy is always greater than zero and with temperature approaching absolute zero ($T \rightarrow 0$), the exergy value approaches a finite value. Assuming that the Sun’s surface emits radiation at a

temperature of about 6000K, the exergy of trapped solar radiation **on Earth**, calculated from the Eq. (15), is $b = 0.9146 \text{ J/m}^3$. For comparison, on Venus, at temperature $T_0 = 740\text{K}$, the exergy of solar radiation is $b = 0.8188 \text{ J/m}^3$ which is 1.117 times less. The energy of solar radiation does not depend on the environment temperature, and the energy of trapped photon gas on Earth or Venus, according to Eq. (7) is $u = 0.9799 \text{ J/m}^3$. The exergy of solar radiation is zero ($b=0$) on the surface of the Sun, which is based on Eq. (15) for $T_0 = T$. Exergy reveals the relativity of the true value of thermal radiation in nature.

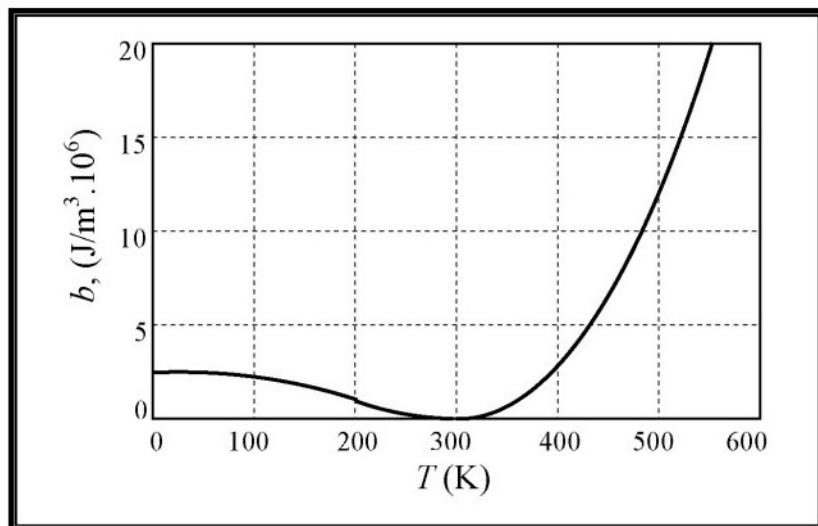


Figure 2. Exergy (b) of photon gas as function of temperature (T), at $T_0 = 300 \text{ K}$.

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Bibliographical Sketch

Ryszard (Richard) Petela received his B. Sc. (1954), M. Sc. (1956), Ph. D. (1962), and Postdoctoral (1965) degrees from Silesian Technology University of Gliwice, Poland. He served as a professor of mechanical engineering at his alma mater from 1956–1984, where he researched and lectured courses in engineering thermodynamics, energy conversion processes, heat and mass transfer, combustion and fuel technology, supervised 73 Ph.D. and M.Sc. dissertations. He co-founded the Polish Scientific School of Exergy, and founded the Silesian Research School of Combustion. He served as the elected President of the Silesian University of Technology, and as a member of the Committees of the Polish Academy of Sciences. He was also the scientific consultant to the Ministry of Chemical Industry and Science on the subject of hybrid gasification process, and was a scientific and technical advisor for steam power stations, for the non-ferrous metallurgy industry, and for the steel industry. He also coordinated the government’s “Energy” and “Coal” research programs. With his research team, he has implemented several technological ideas in steel industry furnaces. He was a member and a licensed expert of the Polish Mechanical Engineers and Technicians Association, the vice-president of the Silesian Section of the Polish Consultant Association, and a member of the scientific boards of four other organizations. He was scientific advisor at the North China Electric Power University at Beijing. He was a member of the American Chemical Society, the New York Academy of Science, and the American Association for the Advancement of Science. For many years he carried out editorial work for the University Research Archives, and was a member of the Editorial Advisory Board of the quarterly *Archivum Combustionis*, under the auspices of the Polish Academy of Science. He was an Associate Editor for the Journal of Solar Energy, and a member of the Editorial Board of the International Journal of Exergy. In 1963-1964 was the British Council Scholar visiting Universities of Sheffield, Leeds, Oxford, Cambridge and Imperial College in London. In 1974-1975 was the visiting researcher at University of Calgary. In 1984-1985 he was visiting Technical University in Vienna. As a former activist in the Solidarity movement in the scientific community, he left Poland in 1984 and immigrating to Canada. He was a visiting professor at the University of Calgary, he served as a research officer of the Alberta Research Council and he was the president of the consulting company Technology Scientific Ltd. His main research interests was focused on the engineering thermodynamics, especially exergy analysis and combustion, but also coal upgrading, waste heat recovery and other. He is the author or coauthor of about 160 refereed articles, authored several text books on combustion technology and book on heat transfer, coauthored pioneer monograph on “Exergy” in Polish and translated into Russian, and authored pioneer monograph on “Engineering Thermodynamics of Thermal Radiation”, developing theory of radiation exergy, in English, translated into Chinese. He holds 12 patents. He was the principal investigator of 72 projects for both industrial and scientific institutions, and presented his research at over 100 national and international conferences.