# Modern Pyrometry

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By

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The physics of the functioning of modern pyrometers, including energy pyrometers (radiation, brightness, partial radiation) and pyrometers of spectral ratio, is considered. Pyrometry methods are analyzed, it is shown that as pyrometry develops, they can be transformed—subdivided into several new ones, or combined into more general methods. Various variants of the classification of modern pyrometers are given—in accordance with the methods being implemented, with the types of radiation receivers, with the design, and with the fields of application. Considerable attention is paid to the methodical and instrumental errors inherent in pyrometry. All the methodical errors known at the time of writing are collected and described, and the ratios that allow them to be compensated are given. It is shown that these ratios, derived mainly in the works of researchers of the second half of the 20th century, are practically inapplicable in modern pyrometry, since they were derived for narrow-band pyrometers, and modern pyrometers are overwhelmingly broadband. As an alternative, algorithms are described that are applicable to pyrometers with absolutely any width of spectral sensitivity, allowing for correction of energy pyrometers and pyrometers of spectral ratio, and with simultaneous consideration of both the spectral dependence of the object's radiance and its temperature dependence. The metrological problems of all pyrometry methods are considered, and ways to solve them are shown. It is concluded that it is necessary to create means of measuring spectral emissivity, and the technical feasibility of creating such measuring instruments is shown. An algorithm for finding the emissivity by five brightness temperatures is described.

The book is intended for researchers, metrologists, engineers and technologists working in the field of contactless temperature measurements, as well as for students studying undergraduate, master's and specialist courses in the disciplines of "Thermophysics", "Technological measurements", "Thermal design of radioelectronic devices", "Metrology" and other related technical and engineering-physical fields and specialties.

*Dedicated to my wife Elena,*
*without whom this book*
*would not have been written*

# CONTENTS

# Preface to the English Edition

Pyrometer temperature measurements are very difficult. Not because it is difficult to get the measurement result on the display of the measuring device. But because this result is most often accompanied by quite large errors, often exceeding 10% of it. And it does not depend on who produced the pyrometer, and how well it is calibrated.

The reason is that there are many so-called methodical errors in non-contact temperature measurements. These errors are a direct consequence of the fact that pyrometers are calibrated according to the BB (Black Bodies), and the radiation spectrum of real measured objects almost always differs from the radiation spectrum of the BB. For this reason, the signals that the pyrometer receiver will generate when pointing at the measured object and at an BB at an equal temperature with it will turn out to be different. That is, even if the pyrometer is perfectly calibrated, and when measuring the temperature of the BB equal to, for example, 1000 °C, it will display exactly 1000 °C on the display, it does not follow at all that you will get exactly the same result on the display when measuring a thousand-degree sheet on a rolling mill. As a rule, the result of measuring a real object will be underestimated. It is precisely because the radiation intensity of real objects is lower than that of the BB, and besides, the magnitude of this underestimation depends on the wavelength of thermal radiation.

The elimination of such methodical errors is one of the most important tasks of pyrometry. If we have the radiation spectrum of the measured object, then we can calculate how the radiation of the object has changed in comparison with the radiation of the BB. Then you can make an amendment that will eliminate the methodical error. But for very many objects that have to be measured, there are no radiation spectra. Their measurement is a very time-consuming task, and requires quite complex measuring stands and installations. Therefore, with the apparent abundance of such information, it is difficult to find the one that is needed in each specific case.

The problem is also that the spectral characteristics of the radiation of objects also depend on their temperature. And this dramatically complicates the task of measuring with pyrometers. As already mentioned, when measuring a real object, the pyrometer underestimates the result in comparison with the actual value of the object's temperature. To compensate for this underestimation, the so-called “degree of blackness” inherent in this object is introduced into the pyrometer before measurement. If this input coefficient is selected correctly, then the mentioned underestimation will be fully compensated, and the pyrometer on the display will display the correct temperature value of the measured object.

And how to choose the correct "degree of blackness" if it depends on the temperature of the object, and the user does not know this temperature? It can be measured with a thermocouple, but then what is the point of measuring with a pyrometer? And often it is simply impossible to use a thermocouple. What should we do then? A correct solution to this problem has not yet been proposed. In practice, the user, based on indirect signs, makes an assumption about what the temperature of the object is, and enters a "degree of blackness" into the pyrometer corresponding to this assumed temperature. But this method of correction not only does not guarantee that the result does not contain an error due to the incorrectly selected "degree of blackness", but also does not give any information about what this error is – 1, 5 or 10%.

The above-described problem of non-contact temperature measurement with strict consideration of the temperature dependence of the radiative properties of objects has not yet been solved. Its solution is proposed by the author of this book, it is set out in chapter 12. The algorithm described there allows not only to take into account the temperature dependence of the spectral emissivity, but also does not require preliminary information about the temperature of the object when measuring.

In pyrometry of the spectral ratio, in order to strictly account for the temperature dependence of the spectral emissivity, it is also necessary to know the temperature of the object unknown in advance. This has also been an unsolved problem until now (however, it has not been formulated due to the high complexity of correcting broadband pyrometers of spectral ratio). The author not only proposed a method for correcting spectral ratio pyrometers with an arbitrary width of spectral sensitivity bands, but also showed how to take into account the temperature dependence of the spectral emissivity. This task has also been classified as unresolved to date. Her solutions are in chapters 8, 10 and 11 of this book.

But there is another big problem. The spectral radiative characteristics of an object also depend on the technological cycle in which the object was obtained, and what is the condition of its surface. That is, even if the user has at his disposal the radiation spectrum of the material obtained or used in its production taken from the literature, there is a high probability that the radiation spectrum of this material in its technological cycle is different from that described in the literature. But without accurate knowledge of this characteristic, it is impossible to completely exclude the methodical error of measuring temperature with a pyrometer. Therefore, the author, having shown the technical possibility of creating devices for measuring spectral emissivity, makes a prediction that the requirement to minimize or completely eliminate methodical errors in pyrometry will inevitably lead to the emergence of this new, currently absent class of devices.

And when will these devices appear? The author makes such a prediction: “Instruments for measuring spectral emissivity will not appear until metrology sets the task of eliminating methodical errors for pyrometry. Today's metrologists have no understanding of the need to set such a task. Pyrometer manufacturers have no idea about this task, it's not their level. They solve, first of all, the task of reducing the cost of devices with the minimum possible deterioration in their characteristics. Scientists in the field of non-contact temperature measurements overwhelmingly do not have knowledge in the field of metrology. Therefore, for many of them, the concept of “methodical errors” is unfamiliar, and they do not even know about the need to exclude these errors.

The situation will change only when metrology, instead of agreeing that there are methodical errors in pyrometry that exceed instrumental errors by an order of magnitude or more, sets the task for the scientific community and production workers to eliminate these errors.”

In chapter 7 of this book, the author, who is one of the leading developers of pyrometers in our country, wrote: "... the improvement of pyrometers in terms of further reducing the instrumental error is pointless at this stage, since it does not lead to an increase in measurement accuracy**. Improving the accuracy of measurements in pyrometry has run into a barrier of methodical errors.** How to overcome it?" The book you are holding in your hands provides an answer to what science still needs to do to overcome this barrier.

Doctor of Technical Sciences,
Professor A.M. Belekliy.

# THE REVIEWER'S PREFACE

This book was written by Frunze Alexander Villenovich, Doctor of Technical Sciences, a man well known both among scientists in the field of pyrometry and among practitioners. He made his first pyrometer more than 30 years ago, and now he is the creator of the Thermokont model range of pyrometers known in Russia. This product range is wide and diverse, and includes over 200 models of devices belonging to two dozen different families. None of the manufacturers represented on the domestic market, including Western ones, has such a breadth of the model range.

As the head of an enterprise producing pyrometers, the author has repeatedly visited industrial facilities where these devices are used. And therefore, he is well aware of the problems of using them, the main of which is the choice of the radiation coefficient. We are talking about the coefficient that needs to be entered into the pyrometer to obtain a correct measurement result. Tabular data roaming through reference publications are very often obtained for devices that have been discontinued today, they are not applicable for new devices for a number of reasons. The selection of the radiation coefficient is often carried out in such a way that at least at one temperature the pyrometer shows a result approximately corresponding to what the thermocouple will show. The errors that accompany such measurements are always quite large, and users are well aware of this.

These errors have been described in pyrometry for a long time. We are talking about errors that occur during measurements with an incorrectly set radiation coefficient. Errors having a similar origin are also found in measurements with two-spectral pyrometers, when they measure objects whose spectral characteristics of radiation change with a change in wavelength. These errors are called methodical, because they are determined by the peculiarities of the measurement method, and not by the imperfection of the instruments. Their descriptions are scattered in various books and manuals. The author of this book has done a great job collecting descriptions of almost all known methodical errors in one of its chapters. There are also described the relations that make it possible to exclude these errors. It would seem that everything is simple, take and use the formulas and coefficients found. But this simplicity is only apparent.

Almost all the ratios are derived under the assumption that the pyrometer is narrow-band, with a spectral sensitivity band of 1-10 nanometers. And the pyrometers produced today have this band from 200-300 to 5-6 thousand nanometers. And for them, these well-known corrective ratios are not applicable. And there are no others. That's why manufacturers carry out the correction of measurement results not in accordance with developed scientific recommendations, but almost intuitively. Realizing that methodical errors devalue the work of developers in their quest to create perfect devices, the author of this book has made an attempt to create a computational model suitable for correcting the readings of any pyrometers—both narrowband and broadband. This attempt turned out to be successful—in 2010, such an original scientific model was described on the pages of several Russian scientific journals. The author also created a set of easy-to-use programs that allow you to perform the calculations necessary for such a correction. This model, as well as the mentioned programs with their detailed description, can be found on this book.

But the described is only a part of the methodical problems in modern pyrometry. It has long been known that the spectral radiative characteristics of objects also depend on their temperature. However, accounting for this dependence for pyrometers with any spectral range width has remained an unsolved problem until now. Using the above model, the author was able to supplement it in such a way that it turned out to be able to take into account the temperature dependence of spectral emissivity.

But for its practical use, real spectral characteristics of the radiation of all those objects that are supposed to be measured using pyrometers are necessary. And for a lot of objects there are none. Therefore, the author makes a prediction that in the foreseeable future there will have to be devices with which it will be possible to easily measure these characteristics. And also showed their technical feasibility.

The quintessence of the book is its 16th chapter, called by the author "Pyrometry of the near future". In it, the author shows that high-precision measurements with pyrometers without methodical errors are not a chimera, but a reality. And it is for the realization of this reality that the algorithms described above have been developed to account for the spectral and temperature dependence of the emissivity. It is for this purpose that devices for measuring spectral radiative characteristics will be created, and an algorithm for the interaction of such devices with pyrometers is proposed for it. In fact, this book is a path to pyrometry without methodical errors, or at least the first of the proposed such paths. The tasks that need to be solved along this path are formulated here, and solutions to the most difficult of them are described. This book "Pyrometry of the XXI century", which you are holding in your hands, is radically different from all previously published books on pyrometry.

Reviewer,
Doctor of Technical Sciences,
Professor V.K. Bityukov.

# INTRODUCTION

This book is devoted, as its name implies, to modern pyrometry. In its construction, it differs markedly from previously published books on the same subject, the writing style of which is more or less academic. We are talking about well-known books [1-9], written mainly in the second half of the XX century.

As the author of this book, I want to explain why it is written this way and not otherwise. To do this, you need to take a short trip into the past. One day in 1986, I, then still a young researcher at the Institute of Optical and Physical Measurements, signed a document with the deputy director. After signing the document, the deputy director said something like this: "Radiation receivers have been developed and manufactured in one of our laboratories. And there are no electronics specialists among the laboratory staff. You know radioelectronics well, maybe you can try to develop pyrometers together with them on the basis of their receivers? These are in-demand devices you won't regret it." After listening to his advice, a few days later I went to this laboratory, got acquainted with its employees and their products. And he began to get acquainted with pyrometry. At that time, I did not expect that in a few years the country would collapse, funding for almost all the work carried out by the institute would stop, and I would have to survive on the sale of hand-made devices. Fortunately, the deputy director turned out to be right – pyrometers were indeed in demand by those industries that were creditworthy at that time, primarily metallurgy.

Our small team developed the Dieltest pyrometers, the first Russian pyrometers based on microprocessors that had just appeared at that time. We had to simultaneously develop new devices, refine those already developed, as well as manufacture, calibrate and sell devices. Demand determined the direction of new developments, and sales indicated whether we understood the needs of the emerging market correctly.

But not only about that. I often had to go to the enterprises that purchased our devices. And these trips provided tremendous food for thought. Pyrometers, which behaved so well during calibrations on emitters-BB (absolutely black bodies), were transformed literally before our eyes in the workshops of our customers. The measurement results very often noticeably did not correspond to those that, in the opinion of factory metrologists and technologists, should have been. My timid words that the device was calibrated with a one percent error in the laboratory caused the factory workers only a slight smile – you never know what you have in the laboratory, you ensure an error of at least 5 percent here.

Together with our customers, we selected the "degree of blackness" introduced into the pyrometer. That is, its value was found at which the pyrometer readings coincided with the readings of the thermocouples. But the technologists grabbed their heads at the same time – the selected "degree of blackness" differed both from the reference one and from the one that had to be inserted into another manufacturer's pyrometer. At one of the enterprises, I was asked: how can it be that there are different "degrees of blackness" for the same material in the same conditions? At that time, I was unable to answer this question clearly. I did not find an answer to it in the books listed above.

Since about 1998, we have started to produce pyrometers of spectral ratio. There was very little information about them in the above-mentioned books, with the exception of book [7]. Both we and our customers focused only on those enthusiastic words about these devices that we found in the brochures of foreign manufacturers. And foreigners were not shy in praising their products.

The pyrometers of the spectral ratio again behaved perfectly in the calibration laboratory. They even allowed measurements to be carried out through thick glasses, or with the outlet of the radiator partially closed. They could measure the temperature of very small objects, their readings practically did not depend on whether they were installed half a meter from the radiator or one and a half meters away. In short, everything was fine with them. But only up to the moment when they got into the factory workshops. And again there were questions. One of the customers tried to believe in his factory laboratory a pyrometer of spectral ratio on a temperature lamp with a ribbon tungsten heater. And he was surprised to find that by about 2500 °C the pyrometer overestimated the measurement result by 200…250 °C[1]. With reference to the known temperature dependences of the spectral emissivity of tungsten, I somehow managed to explain this to him. I saw the same thing later with customers who worked with molybdenum, tantalum,

[1] In the Russian scientific literature, it is accepted that if a parameter changes within certain limits, but it can only have integer values, then a hyphen is placed between the limit values, for example: the event occurs in only 2-3 cases out of 10. If the parameter changes within certain limits, but at the same time it can take not only integer, but also fractional values, then when writing, an ellipsis (3 points) is placed between the limit values, for example: the process temperature can vary within 550 ... 600 °C. The latter means that it can take a value of 573 °C, 562.5 °C, or 585.236 °C (if the device measures with so many digits after the decimal point).

nickel – everywhere there was an overestimation of measurement results by 10-15%. But when I saw a similar understatement at one of the enterprises in Izhevsk, I was amazed. I did not find an explanation for this in the literature, I had to build a physical model myself, right on the go, explaining what happened. The customers looked at me rather askance, apparently thinking – I got out of it cleverly. And I realized that such phenomena need to be described in articles and at least posted on the site so that there is no impression that I “cleverly got out".

I worked for 28 years at the VNIIOFI – Metrological Institute, first at the USSR State Standard, and then at Rosstandart. And, of course, I could not help but pay attention to the fact that the mentioned “degree of blackness” is given in reference publications without the value of its inherent error. And this value directly affects the resulting measurement result (see, for example, (2.1)-(2.3)). That is, one of the values on which the measurement result depends has an indefinite error. Therefore, the result obtained using it should have the same indefinite error. Unfortunately, I did not find a comment on this topic either in the books listed above or in the periodicals. This is just one of the metrological problems of pyrometry, and I came across several such problems, they are described in chapters 13 and 14. All this required a new level of understanding of the role of metrology in pyrometry.

In modern science, metrology in all branches provides verification schemes that guarantee the transmission of units with specified errors, a reference base and methodical support. Its functions also include comparing national standards with those of other countries. And this ultimately reduces measurement errors and increases the reliability of the measured results.

However, a unique feature of pyrometry is that the temperature of objects is measured with BB-calibrated pyrometers, the vast majority of which radiate in a completely different way than the BB emits. What does this lead to? Here is an example. Consider two objects heated to the same temperature, let it be 1300 °C. One of these objects will be the BB, and the other will be a flat surface made of polished tungsten. The radiative characteristics of tungsten have been well studied and are shown in Figure 11.1 in Chapter 11 of this book. Considering Fig. 11.1, it is easy to see that at a wavelength of 0.4 μm, tungsten emits two times less than the BB (the emission coefficient of tungsten here is approximately 0.48). At a wavelength of 1 μm, the emission coefficient of tungsten will be approximately 0.38, i.e. it will decrease up to 2.5 times in comparison with the BB, etc. Thus, when measured with the same pyrometer, the radiation energy that will come to the pyrometer receiver from a tungsten sample will be more than 2 times lower than from the BB. An BB-calibrated pyrometer, when measuring the temperature of a 1300-degree BB, will show, as you might guess, 1300 °C. And when measuring the temperature of 1300-degree tungsten, the measurement result for the described reason will be underestimated (on average by 200...400 °C), even if the pyrometer is perfectly calibrated.

Thus, **the consequence of the fact that pyrometers calibrated according to the BB measure the temperature of objects that emit a completely different way than the BB emits is the appearance of errors unrelated to the quality of calibration of measuring instruments.** The improvement of traditional pyrometers and the reduction of errors in their calibration does not lead to an increase in measurement accuracy. And the development of pyrometry in the last 60-80 years is essentially a search for a way that will make it possible to eliminate such errors[2].

The difference in the radiation of a real object and an BB is called emissivity. It depends on the wavelength of the radiation, and on the temperature of the emitting object, and on the state of its surface, this will be discussed in detail in chapters 6, 7. The radiation recorded by the pyrometer is affected equally by the Planck component of radiation (BB radiation at the same temperature) and the emissivity, because these are two components of a single radiation process of a real object. Science was forced to divide the radiation of an object into these two components, because otherwise it is impossible to uniformly calibrate pyrometers around the world.

And then metrology concentrated on absolutely black bodies, reference means of measuring their temperature, verification schemes with these BB and reference means, and completely lost sight of the second component – the emissivity. There are no means of measuring emissivity, there are no reference tools for their verification and calibration, practically no issues of accounting for emissivity to reduce measurement errors have been worked out. Metrology limited itself to calling these errors, due to the lack of consideration of the emissivity, methodical, and that's all. And continues to improve the BB and reference pyrometers. While the influence of emissivity on the measurement results confuses factory metrologists and technologists. And he urgently demands attention to himself.

It can be said that until now, metrology in pyrometry is the metrology of “black bodies". It is time to extend it to real objects, the emissivity of which is different from unity and changes with changes in the wavelength and temperature of the emitting objects. This is the attempt made in this book. I have described the path that pyrometry has to go through, not its current

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[2] Such errors have been called methodical in science, because the reason for their appearance is a feature of the measurement method used, and not an imperfection of the measuring device used.

capabilities. This is the main difference between this book and the books [1-9].

For this reason, the book lacks detailed reviews of the laws of radiation, various forms of representation of Planck curves, conclusions of relations for the connection of the actual temperature of an object with its radiation or brightness temperature, which have become traditional for the literature on pyrometry, etc. The sections devoted to these issues are deliberately omitted. All these issues are perfectly set out in works [1-9], and specialists should be familiar with them, so there is not much point in repeating.

A large amount of experimental data on the spectral emissivity of real objects is given in well-known books [5,9], as well as in the appendix of the book [21].

Separately, it is necessary to mention a new direction in pyrometry – spectral pyrometry. In 2012, an excellent book was published in Russian [10], comprehensively describing the new methods developed and the results obtained with their help. The author considered it possible not to touch on the measurement methods developed in it, since they are still experimental, undergoing laboratory testing, and it has not yet reached their appearance in production. There is also no metrological support for the described methods. But, nevertheless, experts who are unfamiliar with this book should get acquainted with it.

# CHAPTER 1

# PYROMETRY AS A SCIENCE AND ITS MAIN PROBLEMS

According to a long tradition dating back to [11], pyrometry is considered a set of methods for measuring the temperature of heated bodies by their thermal radiation. However, until the 60s of the twentieth century, pyrometry also included all methods of measuring temperatures exceeding the limit for mercury thermometers ([12]). But in the last half century, contact temperature measurements have not been classified as pyrometry.

However, many still consider pyrometry only as a set of measurement methods based on certain laws of optics and thermal radiation. Pyrometry is usually not isolated as an independent branch of science. And since inertia pyrometry is considered a set of methods, researchers have been engaged in methods up to now – their development, improvement, solving problems arising during the implementation of the method used, and searching for new methods. At the same time, they did not try to cover all the methods at once, and first of all, the problems common to all these methods.

It is time to define pyrometry not as a set of methods, but as an independent branch of science. Accordingly, to generalize the problems of all methods, to see that the problems of all methods have a common origin, and to understand that it is necessary to solve the problems of the branch of science as a whole, then particular problems will be solved. And since the root "... metric" is present in the name of science, the solution of problems should take into account the requirements of metrology.

One of the tasks of this book is, so to speak, the translation of pyrometry from the category of "a set of measurement methods" into an independent branch of science. And the fact that the second root of the name of this branch of science ("...metric") sounds like a purely applied one should not confuse anyone. After all, no one denies geometry the right to be a branch of science, despite the fact that it ends in the same applied "... metric". The set of methods will develop into a science when their particular problems are generalized, the main tasks are formulated, the solution of which will remove the mentioned problems, and when ways to solve these problems are worked out. At the same time, a more general and broader view of the emerging new branch of science will make it possible to move on more meaningfully than before and obtain new interesting results necessary for this movement.

Therefore, let's call pyrometry a field of science that solves the inverse problem in the theory of radiation – determining the temperature of an object by its thermal radiation.

It is known that the dependence of the color of a heated body on its temperature has been noticed by people for a long time. So, in the ancient East, when quenching damask steel, it was heated to the color of the sun at sunset. In metallurgy, up to the XIX century, color temperature scales were used and, heating steel in one or another technological cycle, the blacksmith clearly knew what color it should be brought to before starting processing.

At the end of the XIX century, the first pyrometers appeared – devices that measured the temperature of heated metals. The measurements were carried out by comparing the color of the metal with the color of the heated wire, the image of which was combined in the eyepiece with the image of the measured metal by the optics of the device. And here, for the first time, the question arose of how to calibrate such measuring instruments. According to the author, this moment can be considered the moment of the origin of pyrometry.

For pyrometry, one of the fundamental concepts is an ideal emitter – an absolutely black body, (BB). Its defining physical property is that it absorbs absolutely all electromagnetic radiation incident on it, at any wavelength. When heated, it emits, and it is the radiative properties of the BB that formed the basis of pyrometry.

The concept of BB was introduced by Kirchhoff in the 60s of the XIX century. With subsequent work in the field of thermodynamics, Stefan, Boltzmann, Vin, Rayleigh, Jeans and Planck formulated the laws that govern the radiation of the BB.

It should be noted that the BBT is an ideal radiator that does not exist in nature. At the end of the XIX - beginning of the XX centuries, real physical models of the BB were created – the so-called MBB, black body models. Their radiative properties are very close to the radiative properties of the BB, with an accuracy of units, or even fractions of a percent. MBB is widely represented in metrological laboratories accredited in the field of pyrometry. It was the MBB that became the devices on which pyrometers are calibrated.

However, it was mentioned above that the radiation of real objects in the vast majority of cases differs from the radiation of the BB, both in terms of the spectrum and the magnitude of the emitted energy flux. And this has become a source of measurement errors. The following example is the most illustrative. In a metal pan with a polished outer wall, water is heated to a boil. Half of this wall is smoked for some reason. Measuring the temperature of this smoked part of the wall with a pyrometer, we will get a result within 93-97 °C. Having carried out the same measurement on a clean, polished part of the wall, we will get a result of 40-50 °C less with a smaller one. The reason is that the flow of radiated energy from a polished metal surface is 20...40 times less than from a smoked one at the same temperature.

To minimize such errors, it was suggested that each real object should be matched with a certain coefficient showing how much of the radiation from the BB emits this object. This coefficient was called the emissivity. It was assumed that over time, a database of such coefficients would be created for most materials used in technology, and using them, it would be possible to make measurement errors with pyrometers minimal.

However, everything turned out to be much more complicated. In 1916, Worthing [13] showed that the emissivity of tungsten strongly depends on the wavelength of radiation[1]. Moreover, it also turned out to depend on the temperature of the emitting object. Already in the first half of the twentieth century, it was shown that many metals have similar properties. By the end of the twentieth century, it became clear that for almost any material whose temperature we have to measure with a pyrometer, the emissivity depends on both the temperature of the material and the wavelength of the radiation.

Thus, the heat flow from a heated object is determined not only by the temperature of the object, but also by its emissivity. At the same time, the latter depends in a complex way on both the wavelength of the radiation and the temperature of the object. It was not possible to take into account both components for a long time. Therefore, they tried to recall the influence of emissivity in pyrometry as rarely as possible. Calibrations of pyrometers, as

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[1] In this book, objects whose spectral emissivity varies with wavelength will be called "non-gray", in contrast to "black" and "gray", whose emissivity does not depend on wavelength. The term "selective emitters", which was often used earlier in the Russian scientific literature to designate such objects, is extremely unsuccessful from the author's point of view – selective emitters are actually spectral lamps with a hollow cathode and other sources emitting only at certain wavelengths or only in certain finite spectral ranges. Sources of thermal radiation are not selective in this sense, because they have a continuous spectrum. Calling some of them selective emitters, we use the same term to describe fundamentally different sources, which usually leads to terminological confusion. Therefore, it is better to abandon the term "selective emitter" in relation to sources of thermal radiation and use a different terminology. Since the terms "black body" and "gray body" have been used in radiation theory for more than a century, it is logical to name objects whose emissivity depends on wavelength in a similar way. It is proposed to call such objects "non-gray objects" ("non-gray bodies").

noted, are carried out on the BB. On the one hand, this eliminated the ambiguity of calibrations, but on the other hand, it excluded the emissivity itself from them.

To date, it has not been possible to find a way to metrologically correctly account for its influence, which is acceptable in absolutely all cases, especially for practical applications in real production conditions. They tried to elegantly get rid of this influence by introducing the concepts of radiation, brightness, color, etc. temperatures. This made the theoretical constructions more rigorous, but this did not make it easier for production workers – they were interested in the temperature of the measured object, and not the radiation or color temperature associated with it in an incomprehensible way for them.

Unable to cope on their own, taking into account the influence of emissivity, science shifted the solution to this problem onto the shoulders of users. The pyrometers were equipped with an adjustment body that allows you to change the coefficient entered into the pyrometer, which entailed a change in the measurement result. Many people still call this coefficient the emissivity, creating another terminological confusion. Emissivity is a function that depends on many parameters, primarily on the wavelength of radiation and on the temperature of the emitting object. That is, in mathematical terms, a function of two variables. The coefficient is not a function, but a number. Therefore, it is illegal to call both of them the same term.

Yes, this coefficient introduced into the pyrometer is related to the emissivity of the measured object. But this does not change its essence, it still remains a coefficient. Therefore, it is more correct to call it the radiation coefficient, the blackness coefficient, the degree of blackness, etc. In this book, it will further be called the radiation coefficient.

However, science has not yet given users any clear recommendations on the choice of these coefficients, nor an understanding that for pyrometers with different spectral characteristics, the emission coefficient of the same material under the same conditions may be different. Users most often take data on radiation coefficients from any reference tables, or from the operating manuals of pyrometers, usually compiled according to data from such tables. However, in these tables, as already noted, there is no information about which spectral range the values given correspond to. As a result, there is always a possibility that the user will enter into his pyrometer a value of the radiation coefficient corresponding to a pyrometer with a different range of spectral sensitivity. And this (see Chapter 6) is an additional systematic methodical error, its value can easily exceed 10%, even if a pyrometer with its own instrumental error of less than 1% is used for measurements. Manufacturers are often faced with similar facts, and those who sell pyrometers often have to listen to a lot of unpleasant words about this.

But that's not all. As mentioned above, the radiation coefficients given in the reference literature are given without any inherent errors. That is, one of the main parameters used in measuring temperature with a pyrometer has an indefinite error. And if so, then in accordance with the rules of metrology, the entire result has an indefinite error. The unacceptability of this is obvious, but metrologists try not to notice it.

This is only a small part of the problems associated with emissivity. In fact, all methods have problems and limitations associated with it. And therefore, the further progress of pyrometry as an independent branch of science requires comprehensive consideration of the impact on the result of measurements of emissivity.

# CHAPTER 2

# BRIEF INFORMATION ON THE BASIC LAWS OF RADIATION OF HEATED BODIES: FREQUENTLY MENTIONED CORRELATIONS

The physical basis of pyrometry methods is the laws of radiation of heated bodies, briefly listed in Table 1.1.

**Table 1.1. A short list of the basic laws on which pyrometry is based**

| Law | Content | Mathematical expression |
|---|---|---|
| Energy conservation | The relationship between the radiation flux $Q_f$ incident on the object and the absorbed $Q_a$, reflected by the $Q_r$ and passed $Q_p$ radiation fluxes | $Q_f =$ $= Q_a + Q_r + Q_p$ |
| Planck's Law | The relationship between the radiation flux $E_\lambda$ in the narrow range $d\lambda$, the radiation wavelength $\lambda$ and the temperature of a blackbody $T$ | $E_\lambda = c_1 \cdot \lambda^{-5} \cdot (e^{\frac{c_2}{\lambda T}} - 1)^{-1} \cdot d\lambda$ |
| Wine's law | Approximation of Planck's law at low $\lambda T$ | $E_\lambda = c_1 \cdot \lambda^{-5} \cdot e^{-\frac{c_2}{\lambda T}} \cdot d\lambda$ |
| Rayleigh-Jeans Law | Approximation of Planck's law at large $\lambda T$ | $E_\lambda = \frac{c_1}{c_2} \cdot \frac{T}{\lambda^4} \cdot d\lambda$ |
| Kirchhoff's law | The relationship between the integral radiation flux of an $E_t$ emitting object and the integral radiation flux of a blackbody $E_t^{BB}$. | $E_t / \eta = E_t^{BB}$ |
| Stefan-Boltzmann's law | The relationship between the integral radiation flux of the blackbody $E_t^{BB}$ and its temperature $T$ | $E_t^{BB} = \sigma_0 \cdot T^4$ |

Here $\sigma_0$ is the Stefan-Boltzmann constant: $\sigma_0$=(5.6687±0.001)·$10^{-8}$ W/($m^2$·$K^4$); $c_1$ and $c_2$ are radiation constants, currently they are assumed to be equal to $c_1$=3.7413·$10^{-16}$ W·$m^2$, $c_2$=1.4380·$10^{-2}$ m·K.

## 2.1. Several important correlations

The ratio linking the actual temperature of the object[1] $T_a$ with its measured by a pyrometer brightness temperature $T_m$ ([7, p. 350]):

$$\frac{1}{T_a} = \frac{1}{T_m} + \frac{\lambda}{c_2} \ln \varepsilon_\lambda , \tag{2.1}$$

where $T_a$ is the actual temperature, K; $T_m$ is the brightness temperature measured by the pyrometer, K; $c_2$ = 1.4380·$10^{-2}$ m·K; λ is the operating wavelength of the monochromatic brightness pyrometer, m; $\varepsilon_\lambda$ is the radiation coefficient of the object at the wavelength $\lambda$.

The ratio linking the actual temperature of the object $T_a$ with its measured by a pyrometer radiation temperature $T_m$ ([7, p. 355]):

$$T_a = T_m / \sqrt[4]{\varepsilon_s} , \tag{2.2}$$

where $T_a$ is the actual temperature, K; $T_m$ is the measured radiation temperature, K; $\varepsilon_s$ is the integral emissivity.

The ratio linking the actual temperature of the object $T_a$ with its measured by a pyrometer temperature of the spectral ratio $T_m$ ([7, p. 351]):

$$\frac{1}{T_a} - \frac{1}{T_m} = \ln \frac{\varepsilon_{\lambda_1}}{\varepsilon_{\lambda_2}} \frac{1}{c_2} \frac{1}{\frac{1}{\lambda_1} - \frac{1}{\lambda_2}} , \tag{2.3}$$

where $T_a$ is the actual temperature, K; $T_m$ is the temperature of the spectral ratio measured by the pyrometer, K; $c_2$ = 1.4380·$10^{-2}$ m·K; $\lambda_1$ and $\lambda_2$ are the operating wavelengths of the narrowband pyrometer of the spectral ratio, m; $\varepsilon_{\lambda_1}$ and $\varepsilon_{\lambda_2}$ are the emission coefficients at wavelengths $\lambda_1$ and $\lambda_2$.

[1] In this book, wherever the capital letter *T* is used to indicate temperature, the absolute temperature (in K) is meant. If the lowercase letter *t* is used, we are talking about the temperature in degrees Celsius.

# CHAPTER 3

# PYROMETERS AND THEIR MODERN CLASSIFICATIONS

## 3.1. Pyrometers with disappearing thread

It is claimed that the first pyrometer was invented in the XVIII century by the Dutch scientist Peter Van Muschenbroek. However, the author does not have data on whether this device was created or whether it was used anywhere in practice.

Real pyrometry arose at the end of the XIX century. The first pyrometers, mentions of the use of which can be found in Russian literature, were visual optical devices. In [3] on page 30, with reference to the memoirs of D. I. Mendeleev, it is said about the creation in the 80s of the 19th century in the Urals by D. K. Polenov of an optical visual pyrometer and its successful use at one of the Ural metallurgical plants. The first Le Chatelier pyrometer in Western Europe (developed in 1886-1887) was similar, which is mentioned in [14] on page 79. Thus, optical (visual) pyrometry was the first to be implemented.

The design of the visual optical pyrometer is shown in Fig. 3.1. The brightness or color of the measured body is compared with the brightness (color) of the filament of a photometric incandescent lamp *c*, which in this case is an ordinary converter. The brightness (color) of the filament depends on the current, the value of which is regulated by changing the resistance of the rheostat *f*. The lens of the pyrometer *a* is directed at the incandescent body being measured in such a way that an observer looking through the eyepiece *e* sees the filament of the lamp against the background of the incandescent body.

By changing the current strength in a photometric lamp, the brightness (color) of the filament and the measured body are matched (Fig. 3.2 a). By the way, this is where the common name of such pyrometers in the literature came from – pyrometers with a disappearing thread. Another name for these pyrometers, no less widespread, is optical pyrometers.

Figure 3.2 *b*, *c*, respectively, shows the pictures that the observer's eye sees if the brightness of the filament is greater or less than the brightness of the body under study.

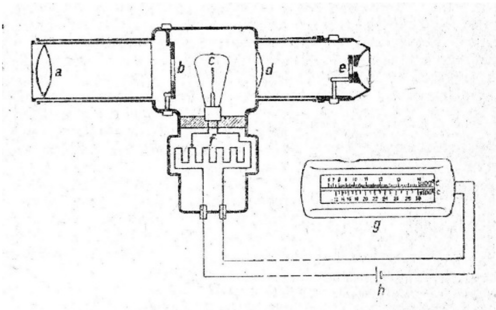
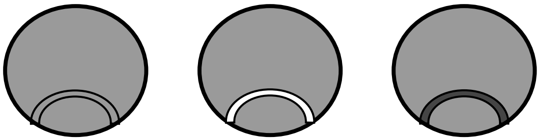



Figure 3.1. Pyrometer with disappearing thread:
*a* – lens; *b* – diaphragm; *c* – lamp with a spiral of comparison; *d* – rotating lens; *e* – eyepiece; *f* – rheostat; *g* – scale of the measuring device; *h* – power supply



*a* *b* *c*

Figure 3.2. Changing the brightness of the filament relative to the brightness of the measured object:
*a* – match; *b* – the brightness of the thread is greater than the brightness of the object; *c* – the brightness of the thread is less than the brightness of the object.

The device is calibrated in such a way that its readings correspond to the measured temperature when the brightness of the filament and the measured object coincide.

The appearance of one of the disappearing thread pyrometers produced in the first quarter of the twentieth century – “Pyropto” by the German company Hartmann und Braun – is shown in Fig. 3.3 [15, p. 317].

In the first half of the twentieth century, disappearing filament pyrometers became very widespread. The book [15], published in 1932, describes 15 different optical pyrometers, including a pyrometer produced in Russia during the First World War (!).

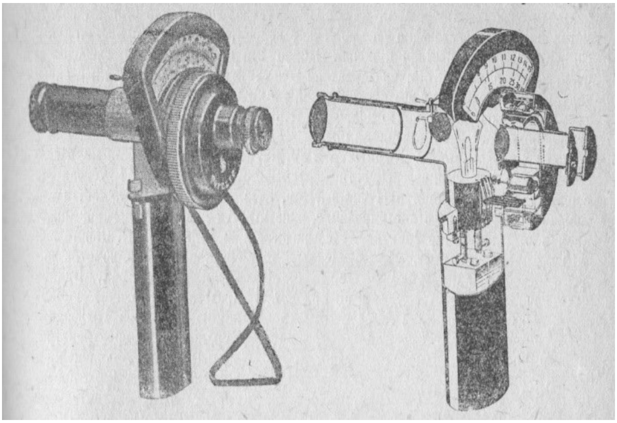


Figure 3.3. Pyrometer with a disappearing “Pyropto” thread from the German company Hartmann und Braun, 1928. ([15])

## 3.2. Energy pyrometers[1]

However, due to the peculiarities of human vision, the described method, based on the perception of color by the eye, has serious limitations in accuracy and convergence (and even more reproducibility!) measurement results. In addition, the operator in such a pyrometer was an integral part of the entire complex that measures temperature, since his organs of vision were involved in the measurement process. Therefore, it was impossible to organize a continuous multi-hour measurement with an optical pyrometer. As a result, it was impossible to continuously monitor the progress of certain technological processes, sometimes lasting for days. In this regard, with the development of the component base, highly subjective visual measurements were replaced by measurements using pyrometers equipped with physical radiation receivers that convert radiation energy into current or voltage.

Initially, pyrometers with a single radiation receiver appeared. The signal from the receiver output was proportional to the energy flow that came to its sensitive area. Therefore, these pyrometers are called energy pyrometers (in contrast to the visual optical ones described above). The block diagram of the energy pyrometer is shown in Fig. 3.4.

[1] Energy pyrometers are understood to be all pyrometers having only one radiation receiver, which determine the temperature by the magnitude of the signal from the receiver, i.e. by the magnitude of the energy flow that came to it

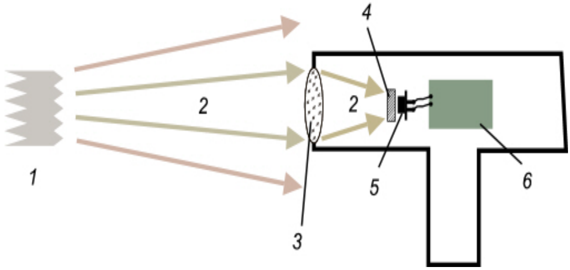



Figure 3.4. Block diagram of the energy pyrometer:
1 – heated object; 2 – radiation flux; 3 – lens; 4 – light filter;
5 – radiation receiver; 6 – electronics node.

Energy pyrometers determine the temperature of an object by the intensity of its radiation at one wavelength (or in one spectral range). They have one radiation receiver, one amplifier, one converter, etc.

It should be noted that the term “energy pyrometers" appeared in the Russian literature relatively recently. Prior to this, when classifying pyrometers into independent classes, separate subclasses of energy pyrometers were distinguished – brightness, full radiation (radiation) and partial radiation. At the same time, the definitions of these pyrometers sometimes differed markedly from different authors [1, 3, 7]. In the English-language literature, at least since the mid–70s of the last century [7], these pyrometers were often combined into a single class of energy pyrometers, which reflected their main common feature - the presence of a single radiation receiver that determines the temperature of objects by the magnitude of the energy flux emitted by them in a particular spectral range.

Energy pyrometers appeared at the beginning of the twentieth century, with the advent of the first receivers. At first, these pyrometers were much less common than visual optical ones. So, in the already mentioned book [15], energy pyrometers are described twice as much as optical ones, only 8 different models.

However, by the middle of the last century, there was a reverse trend – after the appearance of the Radiamatic radiation pyrometer from the American company Brown ([6], Fig. 3.5-3.6), its copies began to displace optical pyrometers. At the time of writing, there are more energy pyrometers in use in the world of different classes, types and levels than all the others combined.