ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

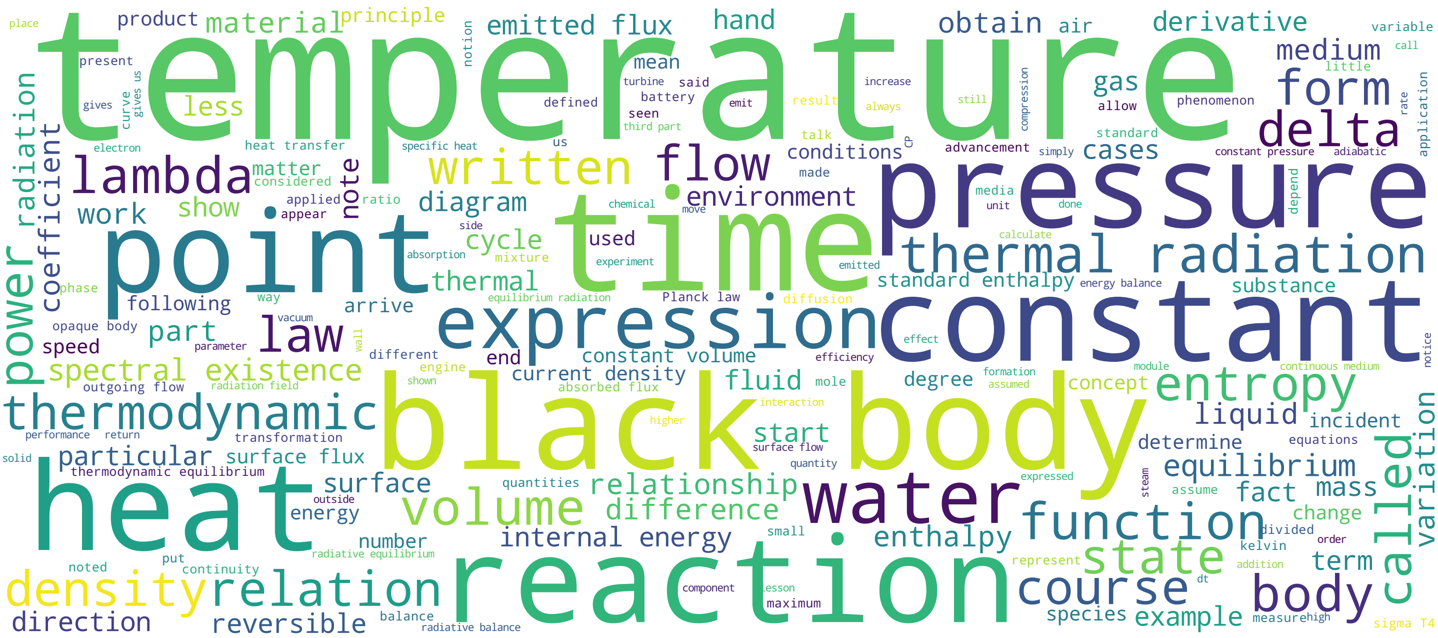
RESCIF
Réseau d'excellence des sciences de l'ingénieur de la Francophonie

Thermodynamique

Rayonnement thermique

Prof. Marwan Brouche

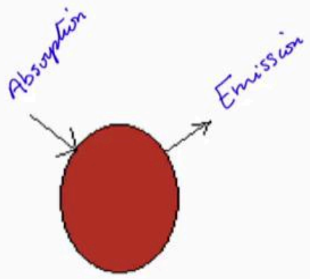
Max Planck, 1858-1947



Video

EPFL

Rayonnement thermique



- Milieux transparents et milieux opaques
  - Emission: OEM dû à la température du corps. Energie interne → énergie radiative
  - Absorption: Energie radiative → Energie interne
  - Réflexion et diffusion: Réflexion → Lois de Descartes
    Diffusion → renvoi étalé
  - Milieu transparent: pas d'absorption ni réflexion ni diffusion
  - Milieu opaque: pas de transmission → rayonnement absorbé et/ou réfléchi, et/ou diffusé

Thermodynamique

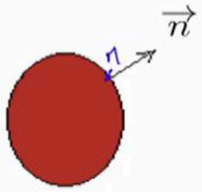
We will now deal with the third part of our course the thermal radiation. A body heated and brought to a temperature T. It will emit an electromagnetic wave. This is the thermal radiation. Thermal radiation is not strictly speaking a thermal transfer energy, because thermal radiation, it can propagate in a vacuum then that thermal conduction needs a material support. However, it will necessarily appear, as the other causes of energy discharges in energy balances. We will now define transparent and opaque media. We will first identify the phenomena concerning the interaction of the matter with an electromagnetic radiation. First phenomenon the show. It is a radiation electromagnetic emitted by a body brought to a certain temperature. the internal energy is thus converted into radiative energy. The second phenomenon is absorption. This is the reverse conversion. The radiation absorbed by the matter is converted into internal energy. Third phenomenon. Reflection and dissemination. The incident radiation can be reflected by the wall in another direction, in the incident media, by interaction with the wall, but this time without absorption. The phenomena involved can be.

Notes

Summary

0m 04s

Rayonnement thermique - Flux radiatif



- Flux surfacique dans le cas du rayonnement — Flux sommé sur toutes les directions autour de $\vec{n}$ (corps convexe)
- Emission $\rightarrow \varphi_e$; Absorption $\rightarrow \varphi_a$; réflexion, diffusion $\rightarrow \varphi_r$
  Flux comptés positivement.
- On considère des corps opaques placés dans un milieu transparent
  $\varphi_{incident} = \varphi_r + \varphi_a \qquad \varphi_{partant} = \varphi_r + \varphi_e$
- Flux radiatif:
  $$\varphi^R = \varphi_{partant} - \varphi_{incident} = \varphi_e - \varphi_a$$
- Equilibre radiatif:
  $$\varphi^R = 0 \Rightarrow \varphi_{partant} = \varphi_{incident} \text{ et } \varphi_e = \varphi_a$$
  Equilibre radiatif $\not\Rightarrow$ Equilibre thermodynamique
  Equilibre thermodynamique $\Rightarrow$ Equilibre radiatif

Thermodynamique

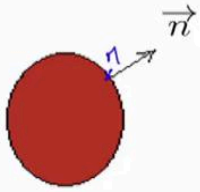
The simple reflection obeying the laws of Descartes, that is to say a radiation which arrives with a certain angle will start again with the same angle to the normal, also at the surface and therefore obeys Descartes' laws. But this return in the medium of incidence can also be under the form of a diffusion which consists in a spread out return in all the directions. Even for a single incidental direction, i.e. a radiation that arrives, it can simply leave in all directions, in the media of incidence. A medium is said to be totally transparent if it fully transmits the radiation it receives. There is therefore no absorption, reflection or diffusion. And a medium is said to be an opaque medium if it does not transmit any fraction of the radiation it receives. The incident radiation is therefore either absorbed, reflected or scattered. These two phenomena can occur simultaneously. The studied bodies are assumed to be convex. Let's take a point M belonging to the surface of the body. And let's take a unit vector a perpendicular to the surface of the body in m the surface flux. In the case of thermal radiation takes into account all directions around of N, both for the incident and outgoing radiation.

Notes

Summary

1m 41s

Rayonnement thermique - Flux radiatif



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Thermodynamique

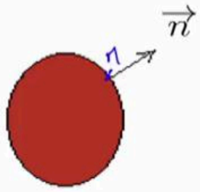
In the case of a convex body that only enters the set of directions corresponds to a half space of solid angle equal to two p. In these cases, we speak of hemispheric flow. Finally, we note. The surface flux corresponding to the emission. And finally the surface flux corresponding to the absorption and fi small earth index. The return surface flow in the medium of incidence by reflection or diffusion. We will. Now positively count all the flows and this for the convenience of the balance sheets. This is equivalent to taking the unit vector normal surface alignment always in the direction of the considered flows, i.e. to the outside for outgoing flows and to the inside for incoming flows. And we will consider the energy exchanges radiating between opaque bodies placed in a transparent medium. And we will reason at a point on the surface of this opaque body. We will define a flow that we will call the incident surface flow. As the power is the surface area of radiation incident on the point considered, the body being opaque to radiation, the incident radiation is either absorbed, reflected or scattered. These processes can of course take place simultaneously.

Notes

Summary

3m 09s

Rayonnement thermique - Flux radiatif



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Thermodynamique

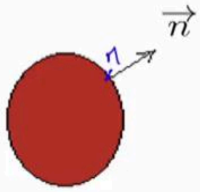
The conservation of energy requires in these conditions that the incident flow is written in the form of finer streams. We also define a surface flow per time that we will call Philippet. This flow accumulates the return flow fi r, but also the flux emitted by the body near the boundary. The conservation of energy implies that the outgoing flow can be written in the form of more finely grained streams. Incident and outgoing flow controls the energy exchanges, translating the interaction between matter and radiation under the conditions mentioned above. We will now define the flow radiative surface that we will call fi grand air, and the radiative flux density is defined by the difference between the flux per time and the incident flux, which is also written as of the difference between the emitted flux and the absorbed flux. This flow expresses the balance between by time and incident flux and effectively measures the surface flux of global radiation at the considered point of the boundary of the opaque medium. The sign of the radiative flux depends on that of the difference between them and phi, i.e. the predominance of emission or absorption.

Notes

Summary

4m 38s

Rayonnement thermique - Flux radiatif



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Thermodynamique

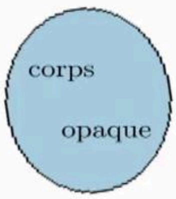
It is counted positively, generally for an emitted flux towards the outside of the absorbing wall of the opaque body. An opaque body is said to be in radiative equilibrium with the radiation fields that surround it if this radiative flux is zero. So the radiative balance implies the equality between the fluxes by time and incident on the one hand, and of course between the absorbed emitted fluxes. On the other hand, noting that this equilibrium condition radiative does not assume a priori a thermal balance, but the thermal equilibrium necessarily implies a radiative equilibrium.

Notes

Summary

6m 06s

Équilibre thermique



$n=1$
Milieu Transparent

- Milieu transparent : $n = 1$

Equilibre thermodynamique et radiatif (ERT)
le rayonnement ERT est caractérisé par

$$du = u_\lambda \, d\lambda \quad [\lambda;\ \lambda + d\lambda]$$

du : densité volumique d'énergie $[J/m^3]$
u_λ : densité spectrale d'énergie $[J/m^4]$

$$d\varphi_{i\lambda} = d\varphi_{p\lambda} = d\varphi_\lambda^0 = \frac{c_0 u_\lambda d\lambda}{4}$$

On pose: $F(\lambda, T) = \dfrac{c_o u_\lambda}{4}$ $[W/m^3]$

Thermodynamique

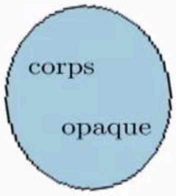
We will now clarify the notion of the equilibrium radiation, for which the equilibrium is assumed thermodynamics of the system at temperature T. The system considered is made up of one or more opaque bodies placed in an isotropic and non-dispersive medium of index n equal to one and of course these media are supposed to be transparent. When we say that the index of the media is one. That is to say that the speed of electromagnetic waves in these media is equal to the speed of light in vacuum. The condition of thermodynamic equilibrium imposes the radiative equilibrium of bodies with the radiation in which they bathe and which occupies the transparent medium. Under these conditions the radiation field that we build from now on. The RT field has special properties. In the range of wavelengths ranging from India lambda, plus lamps in the radiation field. RT is characterized by an electromagnetic energy density d u in the unit and joules per cubic meter such that u. Is written in the form of u lambda by lambda. The u lambda function is called the spectral density of energy, the unit of spectral density of energy and the days or the parameter four.

Notes

Summary

6m 45s

Équilibre thermique



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Thermodynamique

It depends on the lambda wavelength and the equilibrium temperature and it defines all properties of the equilibrium radiation RT. On the other hand, the radiative balance is satisfied for any interval from lambda to specify lambda. So under these conditions, we can write that the flow incident will be equal to the flow per time that we can name now lambda zero son and we show that there is a relation between the spectral density and this zero lambda deficit flux which is written as the form of c0 u lambda of lambda on four. Let f be the lambda of t equal to zero u lambda on four and is called the spectral existence in 1900.

Notes

Summary

8m 14s

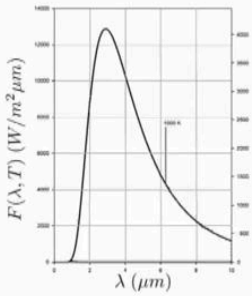
Lois de Planck, Wien, Stefan

- Loi de Planck : $F(\lambda, T) = \dfrac{2\pi h c_o^2}{\lambda^5} \cdot \dfrac{1}{\left[e^{\frac{hc}{k_B \lambda T}} - 1\right]}$

  c_o : vitesse de la lumière dans le vide

  $h = 6,626176\ 10^{-34}\ [J \cdot s]$ const de Planck

  $K_B = 1,38066\ 10^{-24}\ [J \cdot K^{-1}]$ const de Bolzmann



Thermodynamique

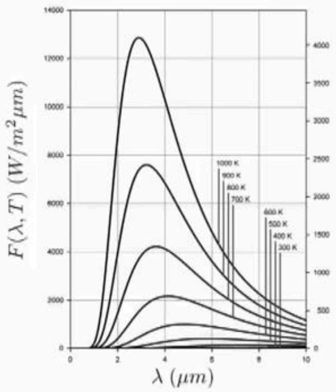
Planck found the theoretical expression of the spectral existence. To obtain this expression, Planck and he made his assumptions on a principle known as of the principle of energy quantification. So we will admit this expression because its demonstration reveals quantum statistical mechanics. If we look at the expression of the existence spectral, there are three constants that are present in this expression. First, the speed of light in a vacuum, but there are also two constants which are fundamental constants of physics. The first is Planck's constant and the second is the Boltzmann constant. If we now plot the variation of the spectral existence as a function of the wavelength, we see that this variation is in bell and the spectral existence will pass by a maximum then 1.1 wavelength lambda that we will call lambda. Max Planck, M.

Notes

Summary

9m 04s

Lois de Planck, Wien, Stefan



- Loi de déplacement de Wien :
- Pour T fixe $F(\lambda, T)$ est maximal pour λ_m tel que $\lambda_m.T \simeq 3000\mu m.K$
- Loi de Stefan:

$$\varphi_i = \varphi_p = \varphi^0 = \int_0^\infty \frac{2\pi h c_0^2}{\lambda^5} \cdot \frac{1}{\left[e^{\left(\frac{hc}{k_B \lambda T}\right)} - 1\right]} d\lambda$$

$$\varphi^0 = \sigma T^4$$

Thermodynamique

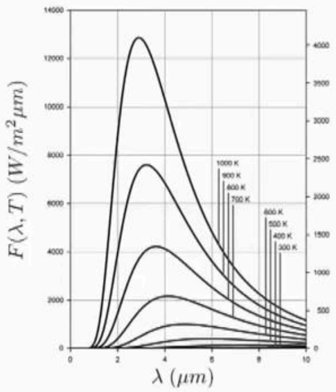
In 1000 893, Wilhelm Vines shows experimentally that the curves of spectral existences for different temperatures always pass through maximums. For lambda wavelengths such that the lambda product M starts equal to 3000 micrometers kelvins which is a constant. For that, we see on the figure opposite that when the temperature increases lambda M decreases in a way to have always the product lambda MT approximately equal to 3000 micrometers per kelvin. So there is displacement. From the spectrum to the short wavelengths when the temperature increases. This is why it is called the law of wine placement. The demonstration of this law was found later. That is, once Planck has found its spectral existence from a theoretical point of view. To obtain the demonstration of this law, it is enough to derive the function of the spectral existence with respect to lambda. Look when the derivative is equal to zero and we find that the derivative of the spectral existence is zero with respect to lambda for a value of lambda set to approximately a constant. Moreover, in 1879, Joseph Stephane found experimentally that the hemispherical surface flux of the equilibrium radiation RT was proportional to the temperature to the fourth power.

Notes

Summary

10m 01s

Lois de Planck, Wien, Stefan



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$$\varphi^0 = \sigma T^4$$

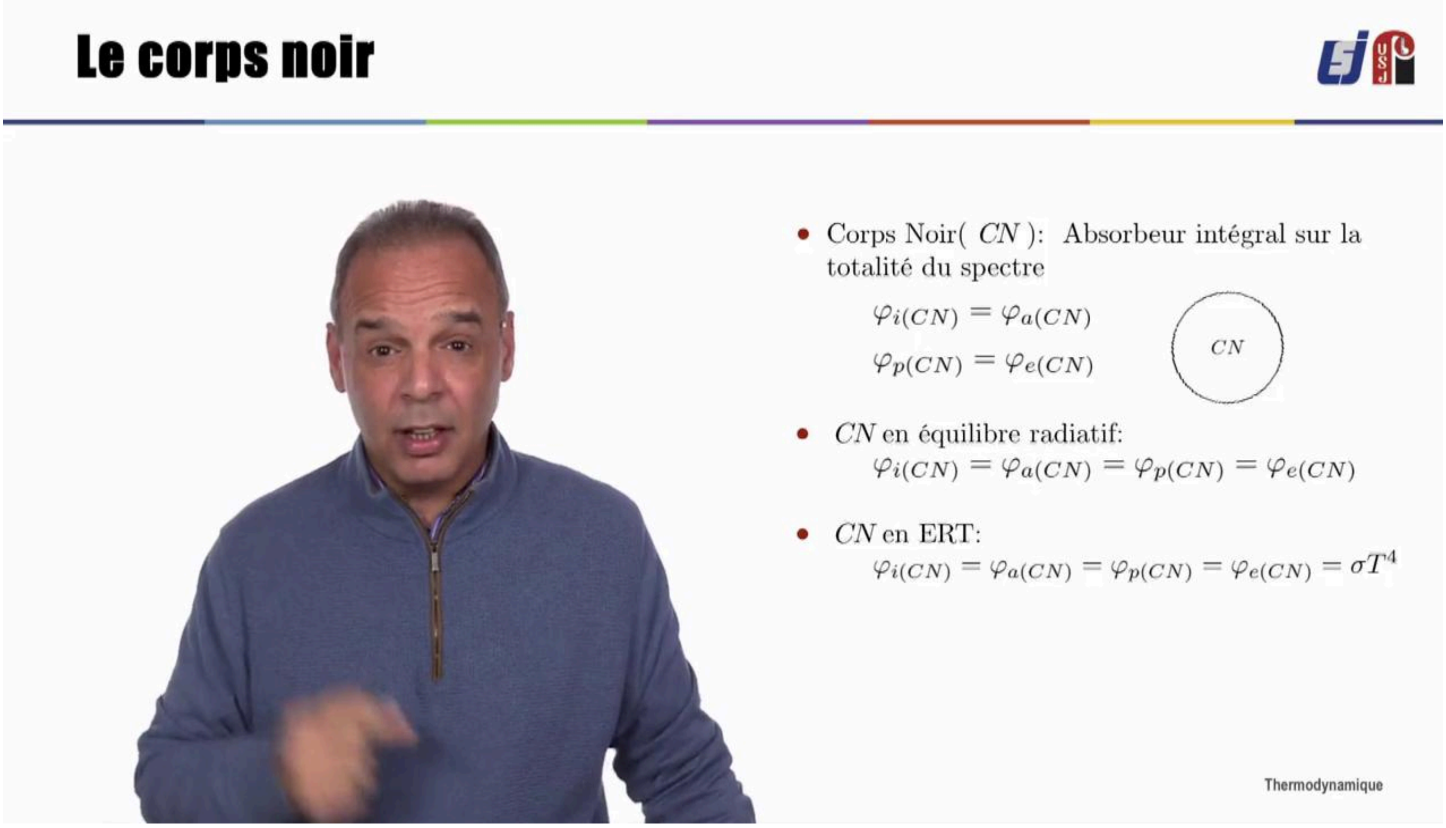
Thermodynamique

As for the city law. This law found its theoretical demonstration once Planck found his theoretical expression of the spectral existence. Indeed, by integrating F of size lambda on the whole spectrum, we find that the hemispheric surface flux is as much for the certain equilibrium radiation is equal to Sigma T4. Sigma is known as the universal constant of Stephane. Its value is 5.67 ten to the power of -8. Stephan's law, which is written as sigma T4, marks the importance of the temperature which intervenes with the exponent four.

Notes

Summary

11m 32s

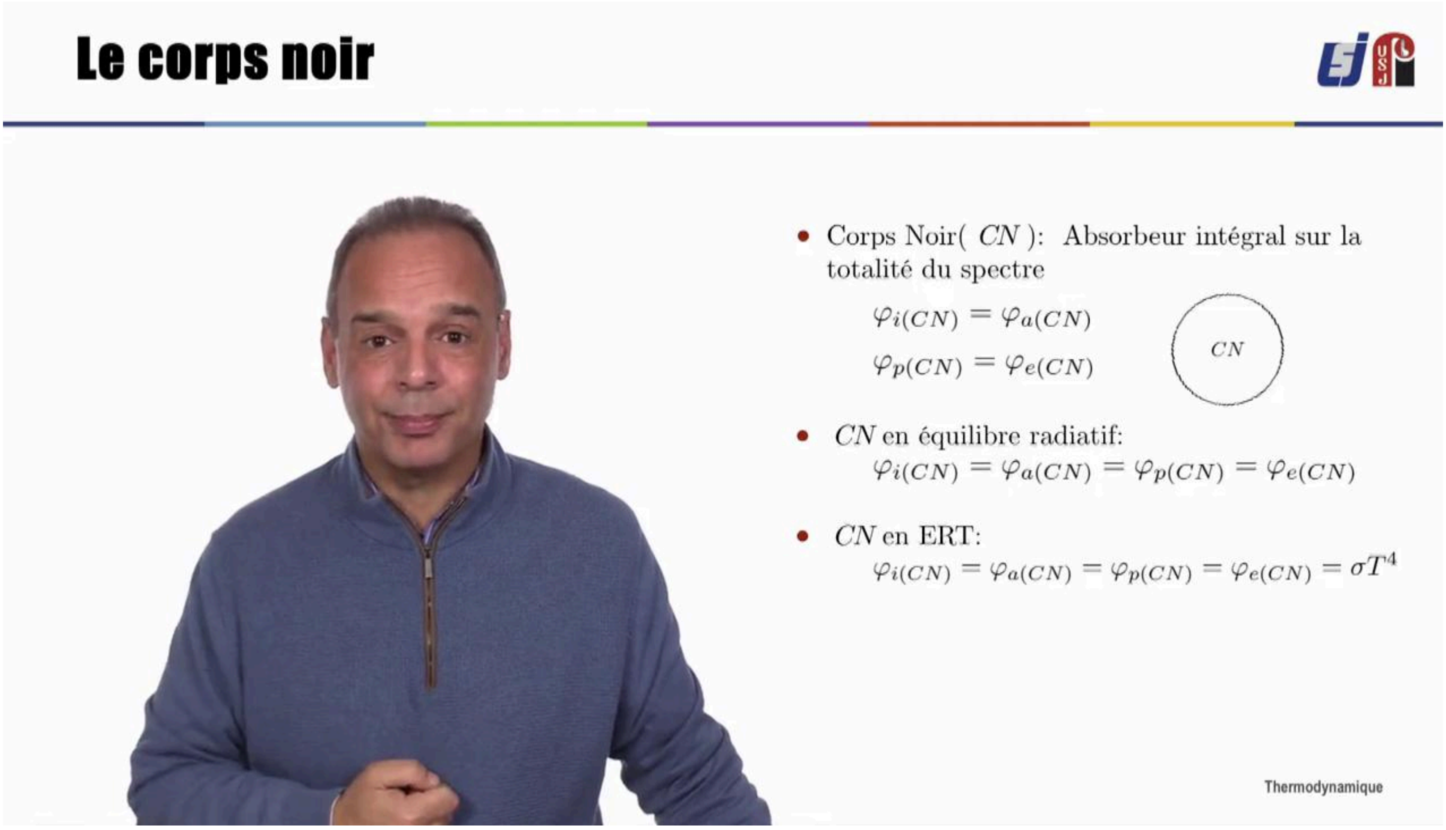


We will now deal with a particular case, the case of the black body. It should be noted that the concept of the black body has played a very important role in physics, on the one hand because he helped to develop the theory of thermal radiation and on the other hand because it helped to put the bases of quantum physics. So, what is a black body? A black body? It is an integral absorber of thermal radiation over the entire spectrum. In other words, if I take a black body and a thermal radiation which arrives on him, whatever the wavelength of this thermal radiation, whatever its direction, it will be absorbed by the black body, i.e. the return flow in the incident medium will be zero. The incident flow will be equal simply to the absorbed flux and the outgoing flux will be equal to the emitted flux. If now the black body, it is in radiative balance. In this case, we will have the incident flow which will be equal to the flux per time which will be equal to the absorbed flux equal to the emitted flux. If in addition the black body, it is in thermodynamic balance. In these cases, we can use Stephan's law. What does that mean? All these flows will simply be equal to a single quantity which is segmented to the power of four.

Notes

Summary

12m 15s



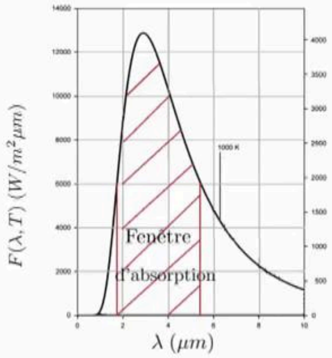
Note that for a non-black body, it has been shown that when this body is in thermodynamic equilibrium, we have inequality between the incident and the outgoing flow. And these two streams are going to be equal at Sigma T4. But in no case these flows will be equal to the emitted or absorbed flows. Why? Because these emitted flows, absorbed flows, will depend on the nature itself, on the atoms that constitute this system. Exception for the black body because for the black body, it has been shown that it is when the black body is in thermodynamic equilibrium, even the emitted flux and the absorbed flux are independent of the nature of the black body. They will be equal to sigma T to the power of four. That's why we talk about the black body.

Notes

Summary

13m 33s

Le corps noir



- Si on suppose les couches superficielles "localement" isothermes (ETL), alors:
  $$\varphi_{e(CN)} = \sigma T^4$$
  (extension de la loi de Planck)
- Loi de Kirchhoff: pour un corps non noir en ETL;
  $$\varphi_{e(CN)} = \varepsilon\sigma T^4 \quad (\varepsilon \leq 1)$$
- Relativisation de la définition du corps noir

Thermodynamique

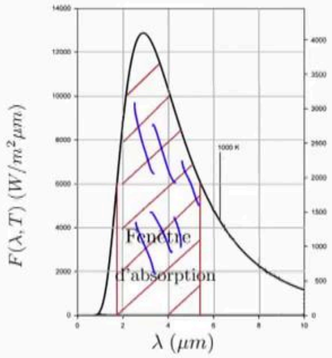
Finally, this part is the thermal radiation. We'll talk about the three important points. First point, the relationship found just before characterizes the emitted and absorbed radiation by the black body, assumed in thermodynamic equilibrium with the radiation that surrounds it and with the opaque body that constitutes the system. Now, we will assume that a black body is not in equilibrium thermodynamic but that the surface layers. These layers on the surface are locally ISO in time. Of course, this does not imply the balance with the other parts of the system, in particular the other opaque bodies with different temperatures. In fact, the radiation emitted and the only fact of the spontaneous emission by the atoms of these surface layers if there is a local thermodynamic equilibrium for these layers whose temperature was the emitted radiation, will still obey Planck's law. For this temperature of quasi-equilibrium, and in these cases, we can write that the flux emitted by these body there is written in the form of sigma T4. This extension of Planck's law concerns only the emitted flux and not the other fluxes. Second point, a general law due to Gustav Kirchhoff indicates that a body emits more as it is better absorber.

Notes

Summary

14m 19s

Le corps noir



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- Relativisation de la définition du corps noir

Thermodynamique

Of course, under these conditions, it is the black body that is the maximum emitter. Moreover, we can notice that when it is to the radiative balance, it will emit a time all that it absorbs. So for an opaque body, not black, in equilibrium at temperature T, we can still write its emitted flux as epsilon sigma T4. Epsilon is called the emotivity of the body and this value, the value of epsilon, will necessarily be less than one. If epsilon is equal to one, it means that we are in the case of a black body. Finally, we'll talk about of what is called the relativization of the definition of the black body. The concept of the black body as an integral absorber is an ideal concept. It is therefore necessary to relativize this notion of the black body to allow the use of these concepts much more broadly than if the strict definition were applied. To do this, you need to place the absorption window of the body on the Planck curve for a certain temperature. If this absorption window encompasses. In large part the Planck curve. We can consider the body as a body black for the radiation R corresponding to the temperature T. Example glass can be considered as a black body for the corresponding RT radiation at room temperature of about 300 Kelvin, i.e. for the thermal radiation emitted by the ground or the atmosphere. On the other hand, it is practically non-absorbent to sunlight.

Notes

Summary

15m 49s

Conclusion

We just finished the third part of our heat transfer course. This third part deals with thermal radiation when heating a body. It will emit an electromagnetic wave. This is the thermal radiation. This thermal radiation has been studied in a particular case. The case where the body is convex, supposed to be opaque, placed in a transparent medium. And on top of that, we assumed that we are within the framework of the thermodynamic and radiative equilibrium. In these cases, the spectral existence of this case of this body is given by Planck's law and from Planck's law, two other laws were deduced. The first is the law of displacement city which says that the spectral existence passes through a maximum point. A maximum wavelength such that the product of lambda m always equals a constant of the order of 3000 micrometers per Kelvin, regardless of body temperature. And the second law, it is Stephan's law which states that the incident flux is equal to the flux carrying over the whole spectrum will be equal to sigma, which is the Stefan constant by the body temperature at power four. And finally, we took the particular case of the black body which is an integral absorber on the whole spectrum. I invite you now to see it go see the video in which an application in engineering is exposed on this thermal radiation field, namely solar collectors.

Notes

Summary

17m 29s