Environmental Science II 6hp ECTS

Physics and Applications

The volcano Etna on Sicily can be observed by listening to the emitted infrasound.

Course contents

The Internet course *Environmental Science. Physics and Applications II* SK183N 6hp, consists of two parts including 4 chapters (4hp) and 2 lab excercises (2hp). It is a continuation of the course *Environmental Science. Physics and Applications* SK182N 6hp.

Part 1 (2hp ECTS) consists of Chapters 1-2 where physical environmental methods that have not been discussed in the course SK182N are introduced, such as waves, sound and noise.

Part 2 (2hp ECTS) consists of Chapters 3-4 where other physical environmental methods that have not been discussed in the course SK182N are introduced, such as electromagnetic waves and radioactivity.

Part 3 (2hp ECTS) consists of “Virtual” lab exercises on the environmental subjects discussed in both Environmental Science courses, SK182N and SK183N. The lab exercises and the apparatuses used are described; lab manuals are presented as well as individual measurement data. This enables the students to perform data analyses and calculations on real events normally obtained in the real laboratories at KTH. An introduction to data handling and measurement analysis is also given.

Chapter 1 gives an Introduction to waves within the field of Environmental science. It starts with a general description of wave propagation, intensity and pressure of the wave. It also gives a general description of heat transfer and how to prevent heat leakage from houses using isolating materials.

Chapter 2 gives an introduction to acoustics and sound, the intensity of sound waves, the dB scale and sound level, noise, infrasound.

Chapter 3 gives an introduction to electric and magnetic properties, electromagnetic waves and it also discusses radiation damage by high intense light and laser light as well, and how to avoid exposure of the eye by intense light. Solar energy and solar parks. Radiation hazards.

Chapter 4 gives an introduction to nuclear safety and problems about decay, storage of nuclear waste as well as new methods in the field of transmutation, i.e. how to convert long-lived radioactive waste to more short-lived matter. This chapter also describes how nuclear methods can be used in environmental science, and details about radiation damage.

The course is split into two sections, the first theoretical part with many solved problems and exam questions. The goals of the course, how to read the material, hints, WEB-hints are given in each chapter.
Each part of 2hp (ECTS), can be done separately.

Part 1: 10 Multiple Choice questions, 5 short problems and 4 extensive problems from chapters 1 and 2: MIN 17 credits in order to pass. (MAX credits: 35 cr).

Part 2: 10 Multiple Choice questions, 5 short problems and 4 extensive problems from chapters 3 and 4: MIN 17 credits in order to pass. (MAX credits: 35 cr).

Part 3: 2 virtual lab exercises. Min credits to pass: 5+5=10 credits. Max credits: 20 credits.

Course goals

- To give an insight in the influence of the society on the environment
- To give an introduction to the use of physical models applied on environmental issues
- To give knowledge about physical measuring methods and instrumentation within environmental science
- To give knowledge about technical solutions concerning environmental science and the use of solar energy
- To be able to solve simplified technical environmental problems also within the field of nuclear safety
- To be able to perform data analysis of environmental measurements by performing virtual lab exercises

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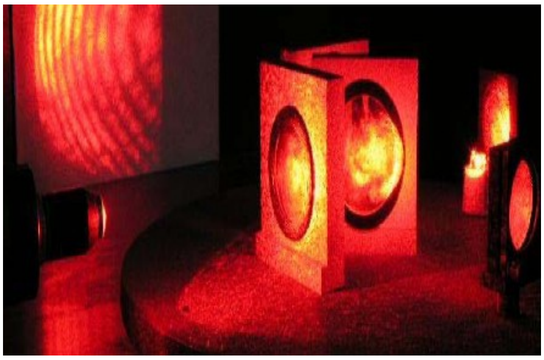
Part I

Chapter 1. Introduction to Wave theory

1.1 Waves and wave functions

Let us imagine water waves moving in the sea. We can observe objects in the water moving up and down. The wave moves in the x-direction, but objects on the surface move in the y-direction. We will try to describe this phenomenon mathematically. By the same technique we will also be able to apply what we derive to acoustic waves as well as light waves. When light waves interact



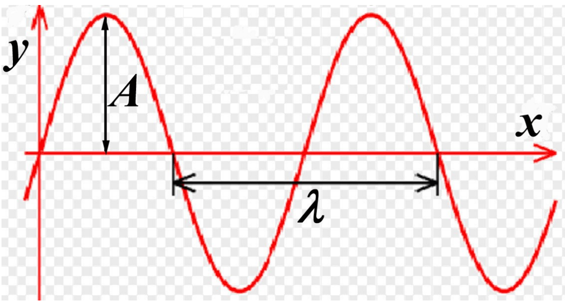
spectacular wave patterns occur. In the picture we can see red laser light giving rise to interference patterns. We will study interference and diffraction using wave functions that we will introduce.

When discussing waves there are some parameters used for the description; the wavelength λ, the frequency f, the angular frequency $\omega = 2\pi f$, the speed of the wave, c for light in vacuum, v for the speed of sound, the wave number $k = 2\pi/\lambda$ (and the spectroscopic wave number $\sigma = 1/\lambda$ in the unit cm^{-1}). A general wave oscillating in the y-direction with amplitude A, moving in the positive x-direction can be described by

$$y = A \cos (kx - \omega t)$$

A corresponding wave moving in the negative x-direction is described by

$$y = A \cos (kx + \omega t)$$



This is an example of a *transverse* wave, characterized by the fact that the particle motion is perpendicular to the wave motion. The wave does not drag the particles with it.

In a *longitudinal* wave, the oscillatory motion of the particles occurs in the *same* direction as the wave propagates. However, the equilibrium position of the particle does not get dragged along with the wave.

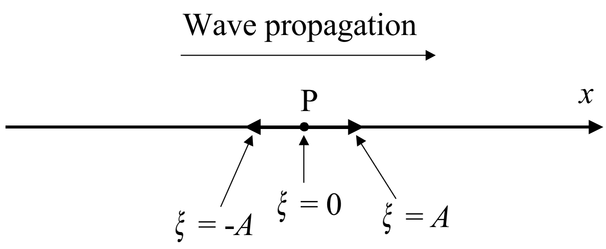
Mathematically, the longitudinal wave moving in the positive x-direction can be described as

$$\xi = A \cos (kx - \omega t)$$

A longitudinal wave moving in the negative x-direction is described by

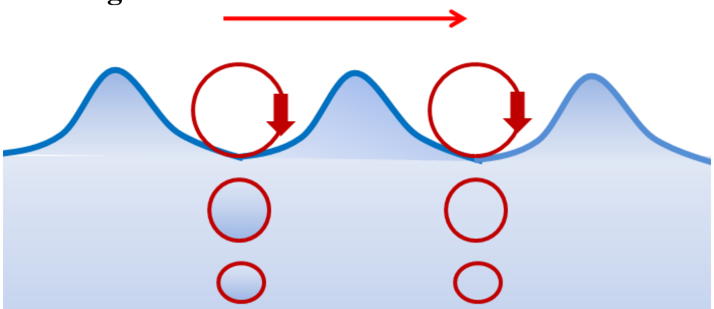
$\xi = A \cos (kx+\omega t)$

ξ represents the *displacement*, i.e. the x-coordinate of a particle in a reference frame, where $\xi = 0$ corresponds to its equilibrium position.



Particle motion: $\xi = A \cos(kx - \omega t)$

1.2 Longitudinal and transverse waves



Inside solid materials both transverse and longitudinal waves can transport energy in the medium, whereas inside fluids, such as gases and liquids, we only have longitudinal waves. In the transverse waves the oscillations takes place perpendicular to the direction of the wave. In the longitudinal wave oscillations takes place in the same direction as the movement of the wave. The above figure shows that near the interface between gas and liquid, the particle motions can be approximated as circular. We can thus say that these surface waves are at the same time transverse and longitudinal.

1.3 Harmonic waves, summary

For a periodic wave, the following relation holds; $v = f\lambda$.
Here v stands for the wave velocity, f for its frequency and λ for its wavelength. It holds for mechanic waves as well as for electromagnetic waves.

Looking at harmonic waves, basic parameters are f, T, ω and λ, where $f = 1/T$, $\omega = 2\pi f$ and $\lambda = vT$. Harmonic waves can be described by trigonometric functions, such as $y = A \cos (kx - \omega t)$, where $k = 2\pi/\lambda$ is the so-called wave number.

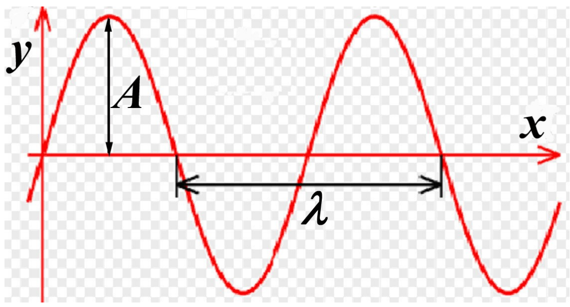
Waves propagate with different wave velocities, v, in different media. Let us look at some examples. First we look at acoustic waves in solids, liquids and gases. The acoustic wave velocities in general:

$v_{solid} > v_{liquid} > v_{gas}$

Examples: Acoustic waves in bulk *aluminium 6400 m/s, water 1500 m/s, air 340 m/s.*
However, light waves behave differently: Light waves:
in vacuum c = 299792458 m/s ≈ 3.00x10^8 m/s, in water 2.3x10^8 m/s in glass 2.0x10^8 m/s.

1.4 Particle velocity

For transverse and longitudinal waves, the particles oscillate locally around their equilibrium positions. The motion of the wave itself does not mean the particles themselves are transported. The particle velocity in transverse or longitudinal wave can be derived by taking the derivative of the particle position as a function of time;



For a transverse wave with $y = A\cos(kx+\omega t)$ we derive the particle velocity as:

$$v_y = \frac{dy}{dt} = \frac{d(A\cos(kx-\omega t))}{dt} = A\sin(kx-\omega t)\cdot(-\omega) = -A\omega\sin(kx-\omega t) \quad ,$$

where the inner derivative is $-\omega$.

The maximum particle velocity is
$v_{y\,max} = A\omega$.

The same treatment also applies for longitudinal waves, the y-coordinate being replaced with ξ.

1.5 Particle acceleration.

In order to get the particle acceleration we have to take the derivative of the particle velocity as a function of time. We start with $v_y = -A\omega\cos(kx-\omega t)$ and end up with:

$$a_y = \frac{dv_y}{dt} = \frac{d(-\omega A\sin(kx-\omega t))}{dt} = -\omega A(-\sin(kx-\omega t))\cdot(-\omega) = -A\omega^2\sin(kx-\omega t)$$

The maximum particle acceleration is $a_{y\,max} = A\omega^2$.

1.6 Wave equation

Looking at the expressions for particle velocity and acceleration, we will be able to derive the so-called wave equation. This equation holds for any type of harmonic wave. We start with the expression describing the particle displacement of the wave:

$y = A \cos (kx - \omega t)$,

It is a function of both position (x) and time (t). We see that we also have the parameters $k = 2\pi/\lambda$ and $\omega = 2\pi f$. If we take the derivative twice on the left hand side of the with respect to t and x, we end up with the following equation, the wave equation:

$$\frac{d^2 y}{dt^2} = v^2 \frac{d^2 y}{dx^2}$$

Here $v = f\lambda = \omega/k$ is the velocity of the wave.

This is a special case of the more general three-dimensional wave equation:

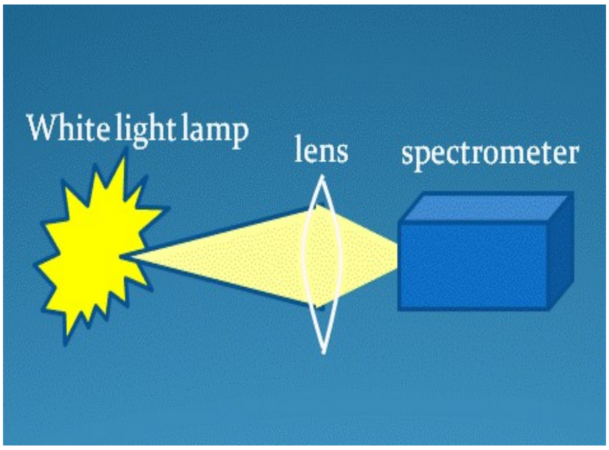
$$\frac{\partial^2 u}{\partial t^2} = v^2 \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right]$$

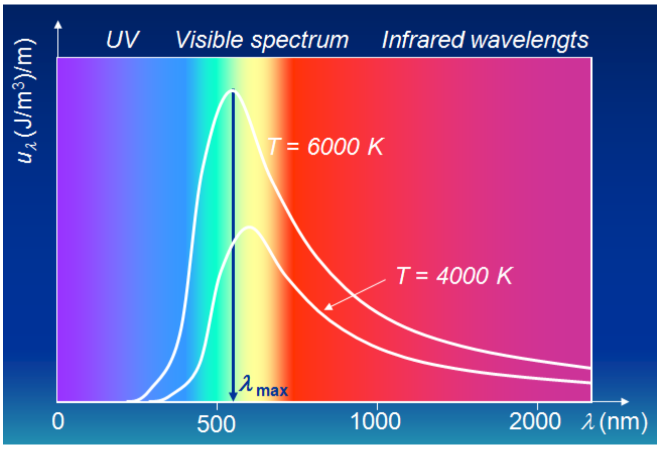
Here, ∂ denotes *partial differentiation.*

1.7 Heat transfer. Insulating materials

1.7.1 Introduction

In the wavelength region above 1 µm, we have the so called thermal radiation region. For instance the solar spectrum above the visible region emits radiation that we experience as heat. Below is shown the solar spectrum (surface temperature 6000 K) and blackbody radiation spectrum from an object with a temperature of 4000 K.





Thermal insulation is used to reduce heat transfer from for example a house to the surroundings. Heat energy can be transferred by conduction, convection or just by radiation. Insulation prevents heat from parting from a house to the exterior, reducing energy losses.

During the major part of the year, it is colder outdoors than indoors in Sweden, why more than 40% of the Swedish energy turnover goes to heating houses. Of course the energy consumption depends on the construction materials of the houses. The large heat losses come from convection, conduction and thermal losses through windows, through floors, walls and ceilings. The ventilation also plays an important role considering heat losses.

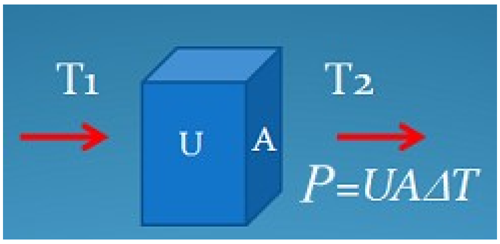
1.7.2 Heat transfer

In all types of heat transfer, temperature differences are responsible for the transfer. It can be due to heat transfer by conduction, convection and radiation. The total transferred power (W, J/s) can be written as:

$$P_{tot} = P_{\text{conduction}} + P_{\text{convection}} + P_{\text{radiation}}$$

The following equation holds for heat transfer through conduction:

$$P = UA\Delta T$$



where we have
P = transferred power [W]
U = heat transfer coefficient [W/m^2·K]
A = area of heat transfer [m^2]
ΔT = temperature difference [K]

1.7.3 Approximation of heat transfer

When performing calculation on houses one normally in a first approximation disregards radiation- and convection energy losses, and just considers heat conduction. In that case we have:

Fourier's law:

$$P_{heattransfer} = P_{conduction} = -kA\frac{\Delta T}{d}$$

where k is the *heat conductivity* [W/m·K], which is related to the heat conduction coefficient according to:

$$k = U \cdot d \quad ,$$

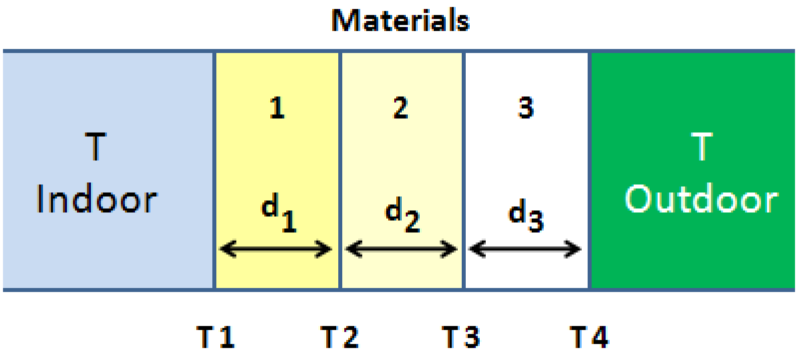
where d = the thickness of the material.

The minus sign in Fourier's law shows how the heat power transfers in the opposite direction of the temperature difference $\Delta T = T_2 - T_1$.

The Table shows *k*-values for different materials used in construction.

Material	***k* [W/m·K]**	**Material**	***k* [W/m·K]**
Air Luft	0,024	Concrete Betong	1,7
Water Vatten	0,60	Brick Tegel	0.6
Iron Järn	75	Pine wood Furuträ (across) (tvärs)	0.14
Copper Koppar	390	Plaster board Gipsskiva	0.13
Glass Glas	0.9	Sawdust Sågspån	0.08
Granite Granit	3.5	Mineral wool Mineralull	0.038
		Glass wool Glasull	0.036
		Cell plastic cellplast	0.014

However, a house completely made in wood would be expensive to heat up. Thus, one builds in several sections with different materials as below:



Through the different materials of the walls, heat transfer takes place by heat conduction, and on both sides of different materials, we have both conduction and radiation. At stationary conditions, the heat flow through the wall is given by:

$$P_{\text{wall}} = U_{\text{wall}} A_{\text{wall}} (T_{\text{in}} - T_{\text{out}})$$

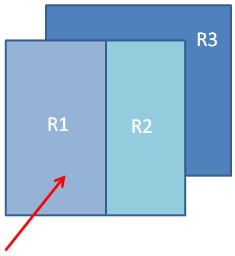
Here U_{wall} stands for the total heat transfer coefficient of the wall.

The inverted value of a heat transfer coefficient is called the heat resistance, denoted by *R* having the unit [m^2·K/W]. One can do calculations on the heat resistance *R* just as an electric resistance in an electric circuit; i.e. we can treat the heat resistance of the figure above just as a number of resistances put in series:

$$\boxed{R = R_1 + R_2}$$

Just as in the case of resistors connected parallel to each other, we can treat heat conductors connected in parallel by adding the inverted resistances:

$$\boxed{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}}$$



Example
Let us have a wall as shown in the figure.
Calculate the total heat resistance of the wall.

Solution
First we calculate the resistance of the two parallel sections. This gives $1/R' = 1/R_1 + 1/R_2$ giving $R' = 1/(1/R_1 + 1/R_2)$. If we now add the resistance of the last section of the wall connected in series with the first section we get $R = R' + R_3 = R_3 + 1/(1/R_1 + 1/R_2)$, which is the answer.

1.7.4 Model for houses

A house consists of walls, floor, roof, windows and doors. In order to minimize the heat losses, it has to be built by selecting the correct materials, and isolation. The total heat losses can be written as:

$$P_{\text{house}} = P_{\text{wall}} + P_{\text{floor}} + P_{\text{roof}} + P_{\text{windows}} + P_{\text{doors}}$$

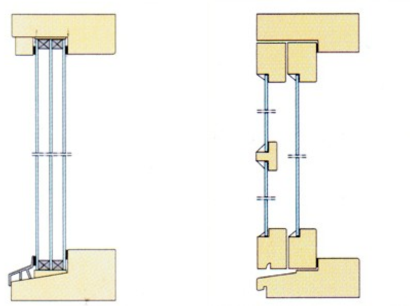
From this we can estimate the total heat losses and be able to calculate a mean value for the *U*-parameter of the house.

$$U_{house} = (U_{wall}A_{wall} + U_{floor}A_{floor} + U_{roof}A_{roof} + U_{windows}A_{windows} + U_{door}A_{door})/A_{house}$$

A normal mean value for a house is $U_{\text{house}} = 0.5$ W/m^{2}K, but can be lowered with good isolation.

1.7.4 Windows

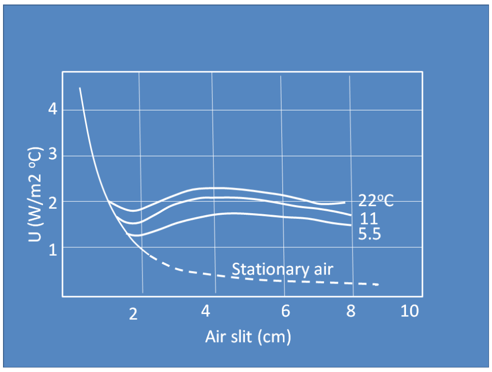
Nowadays, normal windows in new buildings are using three glasses. Earlier two glasses with an air slit were the most commonly used.



Three-glass and two-glass windows

Heat conduction and convection contributes during the heat transfer through the window. The radiation transfer can be neglected. The heat conduction through the air occurs when the air does not move inside the air slit. Convection takes place when air is circulating in the air slit moving upwards close to the warm glass and downwards close to the cold glass surface.

The energy losses are due to a heat exchange process, where the warm air flow transfers its heat to the cold air flow between two glasses.
In the figure one observes the *U*-values for an air slit with different slit widths.



According to the so called Swedish building classification (http://www.boverket.se , Svensk Byggnorm) we have the following equation to calculate the U-value of a house:

$U_{house} = 0.18 + 0.95 \cdot (A_{windows}/A_{total})$ [W/m^2·K]

$A_{windows}$ = Total window area (m^2), A_{total} = Total area of the house (m^2)

Below is shown a Table where the U-values for different windows are shown:

Type of window	***U***
3+3 mm Float glass 1+1 two glasses	2,8
3mm Float glass + 4mm Energy glass 1+1	1,8
3mm Culture glass + 3mm Float glass 1+1	2,8
3mm Culture glass + 4mm Energy glass 1+1	1,8
3mm Float glass + 2-glass isolation 2+1	1,7
3mm Float glass + 2-glass isolation, energy 2+1	1,4
3-glass Isolation window	1,9
2-glass Isolation window	2,8

Float glass, ordinary glass. The name comes from the fact that the glass floats out under production.
Energy glass, heat reflecting glass by a thin layer of tin oxide on the glass surface.
Isolation glass, tight connected glasses with aluminium bars.
Culture glass: Machine made glass, not completely plane. Looks like "old glass".

As we have seen earlier $U = kd$, where d is the thickness of the material.

In two- or three-glass windows, the volume between the panes can be filled with a heavy gas that is more viscous than oxygen and nitrogen in order to increase the insulating performance. Higher viscosity reduces convective heat transfer, as well as reducing the heat capacity portion coming from rotational degrees of freedom. Argon (argon has a thermal conductivity 67% that of air), krypton (krypton has about half the conductivity of argon) or xenon (about 1/3 the conductivity of argon). Some window manufacturers also offer sulfur hexafluoride as an insulating gas, especially to insulate against sound. It has only 2/3 the conductivity of argon, but it is stable, inexpensive and dense.

1.7.5 Ventilation

Normally, a person at rest needs 0.25 litres of oxygen per minute, and when working at the person's maximum, around 10 times more is required. An exchange of half of the air volume of the house in one hour is normal for a house. In older houses, unwanted ventilation can be present.
In windy days, there is an over-pressure on the windy side and an under-pressure on the other sides of the house. Also temperature differences between indoor air and outdoor air can result in a pressure difference on the walls that can influence the unwanted air exchange.

1.7.6 Insulation

A nice way to reduce the energy losses in a house is of course to insulate the walls and roof with a material with a low heat conduction coefficient. When you have insulated the walls you should reach $U_{house} \approx 0.30$ W/m^2·K, and for floor and roof $U \approx 0.25$ W/ m^2·K.

Example
If we want to have value of $U \approx 0.25$ W/ m²·K of a roof, using mineral wool, how thick should the layer of mineral wool be?
Solution
Mineral wool has $k = 0.038$ W/m·K and with $k = U \cdot d$, we get $d = k/U = 0.038/0.25$ m $\approx$ 1.5 dm.

1.7.7 Heat transfer through convection

In many cases, like radiators inside houses, the dominating mechanism of heat transfer is convection, i.e. heat transfer from a warm body to cooler streaming air momentarily in direct contact with the radiator (*free convection*). Convection efficiency can be greatly enhanced by mechanically blowing the air so that a larger volume per time unit will get in contact with the hot surface. This is called *forced convection*.

Mathematically, free convection can be approximated as: $P_{convection} = hA(T_2 - T_1)$, where h [W/ m^2K] is the *convection heat transfer coefficient*. Typical values for free convection in gases are around 2-20 W/m^2K and in liquids 50-1000 W/m^2K. The corresponding values for forced convection are about an order of magnitude higher. For a surface with area A it is possible to define a convection heat resistance $R_{convection} = 1/(hA)$, in analogy with conduction resistance.

Example: A radiator has a total surface area of 3 m^2 and contains water at a temperature of 50°C. Calculate the convective energy flow (W) from the radiator to the room air at a temperature of 20°C.

Solution: Taking $h = 5$ W/m^2K, we get $P_{convection} = 5*3*(50–20) =$ <u>450 W</u>. A three-room flat normally contains about six radiators. This means that the average heating power wintertime will be about 2.7 kW, i.e. about 65 kWh/day or about 2000 kWh/month.

1.7.8 Heat transfer through radiation

A black body with temperature T_2 placed in a surrounding at temperature T_1 radiates and receives energy according to $P_{radiation} = \sigma A(T_2^4 - T_1^4)$, where σ (5.67*$10^{-8}$ W/m^2K^4) is the *Stefan-Boltzmann constant*. Painted bodies like radiators can often be approximated as black bodies. However, for bodies coated with highly reflective surfaces (e.g. metal) radiate less than a perfect black body.

Example: Calculate the radiative power of the radiator in the previous example, assuming it can be treated as a perfect black body.

Solution: The effective radiative surface area is now 1 m^2. This gives $P_{radiation} = \sigma A(T_2^4 - T_1^4) =$ $5.67*10^{-8}*1*((273+50)^4-(273+20)^4)$ = <u>200 W</u>.