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Physical data

The 4 principles of thermodynamic

First principle
Heat (thermal energy) never disappears and cannot be created: it can only be transformed or it can be transferred but it always remains. We can capture heat, store it, distribute it.

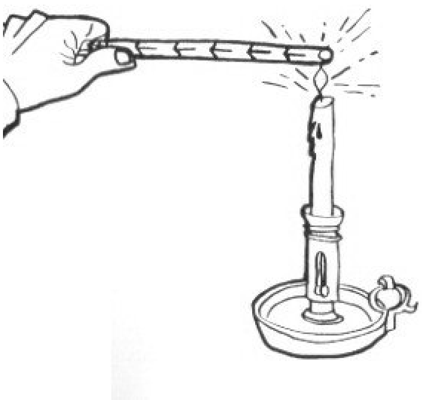
Second principle
Cold does not exist; cold is only an absence of heat, it means everything is more or less hot. Even ice!

Third principle
Heat moves always from the hotter to the colder. There can be an exchange of heat only if there is a difference of temperature.

Fourth principle
The exchanges of heat strive to bring back equilibrium, i.e. the same temperature everywhere, i.e. when there is no loss and no gain (no exchange) anymore. This state of perfect equilibrium is never reached because conditions are changing all the time.

The 3 types of thermal exchanges

First type of thermal exchange: conduction
Heat moves through direct contact through matter, going always from the hotter to the colder.
With conduction, matter remains immobile while heat moves through it.
Materials resist more or less this transfer of heat through them; it is why some materials are good conductors for heat, like steel, and others are bad conductors for heat, like wood or any insulating material.

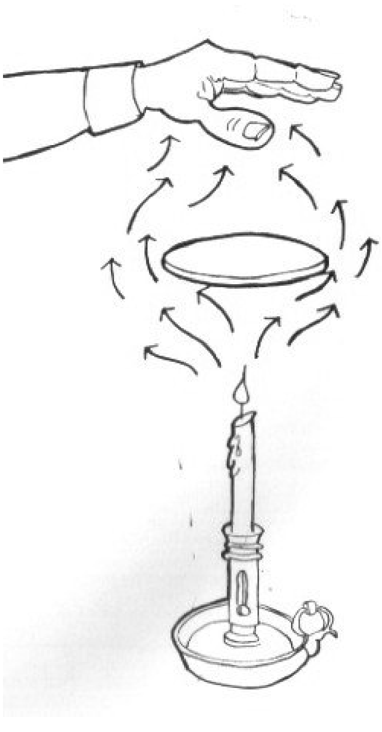


Particularity: While heat goes through a material, it has to heat up this material and therefore heat diminishes slowly.

Experience: If you touch the hot plate, you burn yourself. If you hold a bar of metal at one end and you put the other end in the fire, heat will run along the bar (i.e. heat up the whole bar) until it reaches your hand and until the heat becomes unbearable for your hand. Conduction leads heat through the bar to your hand.

Second type of thermal exchange: convection

Heat can be transported by a fluid (water or air). If air gets some heat from any source, it becomes hotter: hot air (because it expands) becomes lighter and has a tendency to rise, while cold air (because it contacts) becomes heavier and has a tendency to fall. According to the principle of Archimedes.
If air gets hot, it will start to move up on the hot side while the rest of the air in the same container (or room) is pushed down near the other wall. It creates a natural circulation movement until no more heat is added, then the air stratifies in layers, the hottest on the top (hot air is lighter), the coldest at the bottom (cold air is heavier), until the temperature equalises in the fluid (through conduction). The same happens with water or any fluid.

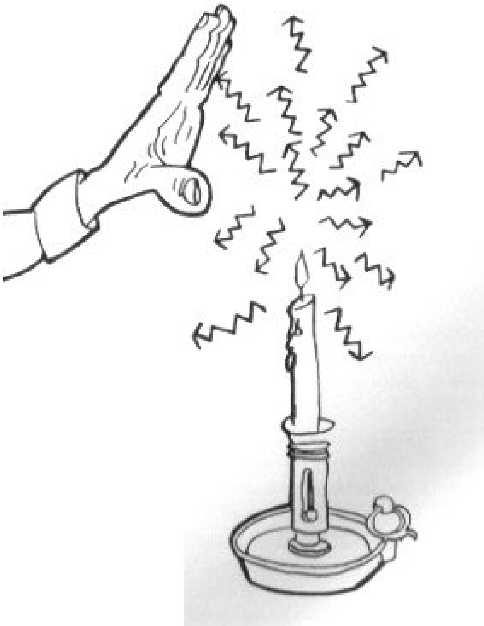


Particularities: With convection, the fluid (air or water) rises on the hotter side and falls on the colder side of the container (or room). If the difference of temperature between the side wall and the fluid is big, the heat exchange happens quicker and the movement of the convection is quicker too; a quicker convection participates to increase still more the heat exchange (if you blow on your spoon, your soup cools more quickly down). Therefore the heat transport increases with the difference of temperature between the side wall and the fluid for two reasons: a quicker heat exchange and a quicker transport... until it stabilises. With convection, because heat creates a movement in the fluid, it is not heat which flows through the fluid but the fluid itself which moves and transports heat.

Experience: If you are above a stove, you feel the hot air rising from around the stove. Marilyn Monroe with her floating skirt over the hot draft, that's convection!
In your eskie, you put the drinks first and then the ice on the top. The hot air rises from the drinks, gives its heat to the ice, cools down and falls back down to the drinks where it takes the heat from the drinks, and rises, etc... The convection is the basis of the cooling process. But if you put the ice first and the drinks on the top, there will be no convection; there will be stratification with the cool air on the bottom and the hot air on the top, and no exchange will happen; the drinks will remain hot on the top while the ice will remain cool on the bottom, except a small effect of conduction where they touch each other.

Third Type of thermal exchange: radiation

Heat travels through space on a straight line, as a beam: the sun beams for instance. These radiations travel through empty space or a light fluid until they meet resistance (a solid body).
Radiations bring heat into the body they meet which will absorb part of this heat. Each body absorbs heat from radiations if its temperature is lower than the one of the radiations source and each body radiates heat according to its own temperature. That is a very important characteristic for heat transfer.



Particularity: Although we also radiate and receive heat radiations from everywhere, we do not feel the heat we radiate or the heat we receive if the difference of temperature with our environment is small, for instance between us and the surrounding walls. With radiation, heat is moving, and not the fluid it is going through. Because of the small density of the fluid or the void it is going through, heat does not loose much of its strength: it does not need to heat up the support to its own temperature, like for conduction.

Experience: If you stand beside the stove, you feel the radiations of its heat, and if you put a screen between the stove and you, you stop feeling it. The same in the sun. If you stand near a cold wall, you feel how it drains heat out of your body, because heat goes from the hotter (your body) to the colder (the wall).
If you put a closed container filled with water outside by a clear night and you expose it to the night sky but protect it from any radiation of the direct environnement, for instance by building a kind of well around it with reflective walls, you could almost freeze the water of the container if the ambiant temperature is not to high, because the radiations from the container (about 20 °C) to the back of the universe - which is very cold (-273 °C) - will discharge the heat which is contained in your water.

(the 3 drawings are by David Wright: "Sun, Nature, Architecture")

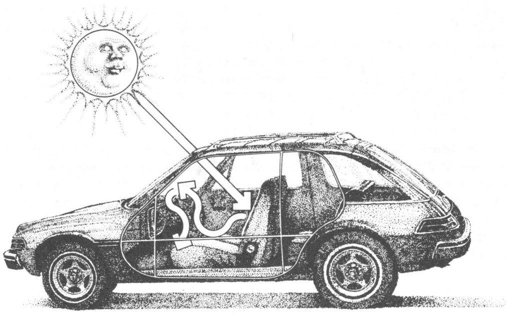
The Glasshouse Effect

Each material radiates and absorbs radiations from other bodies; the wave length of these radiations varies according to the temperature of the radiating body.

If the temperature is high, the wave length is short. The sun is very hot (6'000 °C) and the wave length of its radiations is very short.
Our body are not so hot (only 36.5 °C) and it radiates with a longer wave length. The same for our surrounding, unless it is extremely hot.

Each body has its own absorption coefficient and its own radiating coefficient, which are both in fact equal and constant, and are determined by the quality of the surface of this body.

Glass lets go only short waves (sun light) through, but not long waves (radiation from the surrounding)



(drawing by E. Mazria, The passive solar Energy Book")

In a glasshouse, the sun light (short wave length) penetrates through the glass and hits the floor and the walls which become hotter, and start also to radiate, but with a lower wave length. This is a property of the glass that it lets go only the short waves (sun light - high temperature of the sun) through and does not let go the longer waves through (radiations from the walls and floor - lower temperature). It means that the incoming heat from the sun (short wave) can penetrate in the glasshouse and can heat up the materials, while the radiations from the walls and floor can no more go out since they are a long wave. Heat is captured and temperature increases in the glasshouse.

The glasshouse effect needs 3 elements:

1) radiations from a very hot source (sun),
2) an inner material which is exposed to this incoming radiation, absorbs it, gets hot and starts also to radiate: this material plays a very important role because it transforms the short waves in long waves which cannot escape any more, because of the characteristic of the glass. If this material is a good absorbent, the effect is improved, because it will absorb more than a poorly absorbing material, and also radiate as much as it absorbs.
3) and, between the heat source and the material, a glass wall which lets the heat from the very hot source come in, but does not let the long waves radiations from the surrounding come out.

Experience: if you leave your car in the sun, it will become very hot inside. If you cover the windows from outside with a protection, the heating effect through glasshouse effect will stop.

The 5 Relations between Heat and Temperature

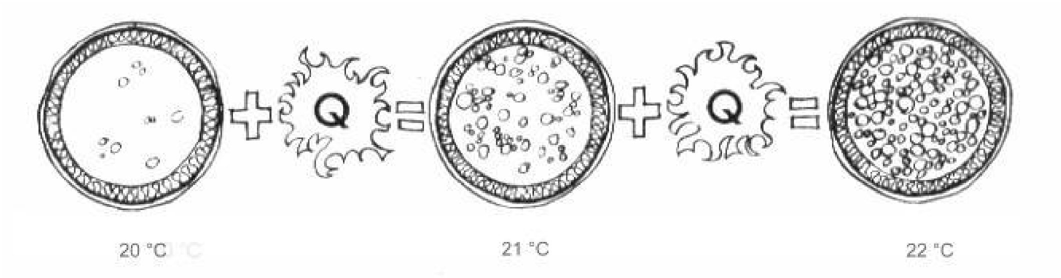
1) Heat and temperature

- One measures heat, which is an energy, in Joules (J) or in calories (cal) - see Physics Units - It indicates a quantity of heat, i.e. a quantity of thermal energy. When this energy is communicated to a body, its temperature increases. If more energy is transmitted, its temperature increases proportionally to the quantity of energy transmitted.
- One measures temperature in degrees (°C or °K) according to a scale which is defined arbitrarily once for ever. For instance, for the Celsius scale, it has been decided that 0 °C is the temperature of melting ice and that 100 °C is the temperature of boiling water. For the Kelvin scale, it has been decided that 1 degree °C is equal to 1 degree °K and that 0 °K is the same temperature as -

273 °C which is the theoretical temperature of the "back" of the universe (the absolute zero, i.e. nothing in the world can be colder).

2) Thermal energy and thermal power

- Thermal energy is measured in Joules (J). It is a total quantity of energy you can receive, or you need to capture, or you have at disposition and you can use. If you compare it with water, it is like the quantity of water you have in a container.
- The increase in temperature of a material is in relation with a given quantity of added heat or thermal energy. To get this quantity of thermal energy, you need a flow of energy (an intensity), during a given duration of time; this flow of energy is called thermal power, and is measured in Watt (W) - See Physics Units.



(drawing by David Wright)

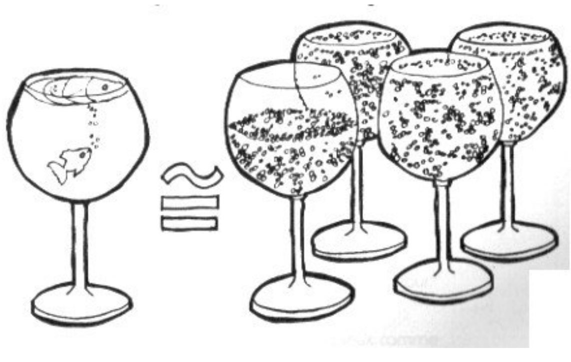
We have the following relation between thermal energy and thermal power: a thermal power (in W) will last for a given time (number of hours) and provide a quantity of energy (in J): 1 J = 1Wh or 1 W = 1 J/h, i.e. one Watt is the thermal power of an energy flow which will bring the total quantity of energy of one Joule if it lasts for one hour. If you compare the flow of energy to the flow of water, the thermal power (in W) is similar to the flow in litre/min. The quantity of thermal energy we receive from the sun is measured in Watt/m^2; if you expose a bigger surface (in m^2) to the sun, you capture a bigger quantity of energy (in J) during a given time.

3) The specific heat C of a material

The specific heat C of a material (in J/kg °C or in kcal/kg °C) is the quantity of heat needed to increase the temperature of 1 kg of this material by 1 degree. It is also the quantity of heat this material will restitute when its temperature drops by 1 degree. For water, the calorific heat is 1000 cal/kg °C, it means you need 1000 cal to increase the temperature of 1 kg of water by 1°C. For concrete it is only 156 cal/kg °C and for steel only 120. This data is very interesting because it means that 1 kg of water can store 6.4 times more heat than 1 kg of concrete.

4) The calorific capacity of a material

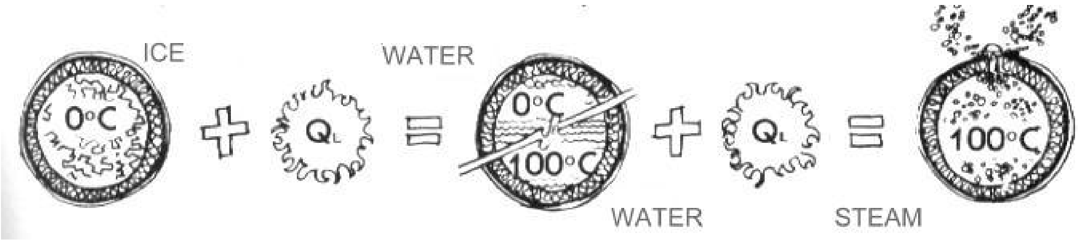
The calorific capacity is the same as the specific heat but related to volume instead of to weight. It means that it takes into account the specific weight of the given material (i.e. the weight of this material per volume unit). You can therefore calculate the calorific capacity of each material by multiplying the specific heat by the specific weight of this same material. We said that 1 kg of water can store 6.4 times more heat than 1 kg of concrete, but concrete is 2.3 times heavier (it means denser) than water. It means then that the calorific capacity of water is only 2.7 times higher than the one of concrete.



Water contains 3.5 times more heat than the same volume of sand. (drawing by David Wright).

5) The latent heat

The latent heat is the quantity of energy (in J/kg or in cal/kg) which is needed to change the state of a material from solid to liquid or from liquid to gas without changing its temperature. It is for instance 80 kcal/kg (334 kJ/kg) for water. It means you need 80 kcal to transform 1 kg of ice into 1 kg of water at 0 °C, without changing its temperature!



This data is very interesting because it shows the quantity of energy the change of state can consume or return. For instance, the evaporation of water is used for cooling and each kg of water which evaporates absorbs 80 kcal which are taken in the surrounding air, of which the temperature drops according to the specific heat (cal/kg °C) or the calorific capacity of air (in cal/m^3). You can see how theses data can be used practically. (drawing by David Wright)

The 6 characteristics of heat transfer by conduction

1) The building envelop loses heat

The building envelop (exterior walls, windows, roof, groundfloor) is made out of different materials (brick, glass, wood...) which cannot retain completely the heat inside when it is cold outside. There is always a loss, and the importance of this loss depends on:

- the insulating capacity of the materials in use - an insulating material (polystyrene) resists to the transfer of heat, while a good conducting material (metal) allows an easy heat flow.
- the thickness of each of the materials - if the material is twice thicker, it will let go through only half of the heat.
- the surface exposed to the difference of temperature - if an element is twice bigger it will let go twice the quantity of heat.
- the difference of temperature - if the difference of temperature doubles, the heat loss will double too.

The total loss of heat out of the building indicates how much heat must be produced or captured to replace it. It is a energy power, because it is related to time: how much heat in an hour or in a day.

2) The heat conductance, the heat conductivity and the heat resistance of materials

Conductance: Each material has a different conductance for heat, i.e. its capacity to conduct heat. A light material which is made of a lot of little cavities will be badly conductive for heat, because heat has to go around each cavity, which makes the way longer, and the air contained in the cavities will retain the heat flow. This material will be insulating, like wool for instance. On the opposite, a very dense and heavy material will be a good heat conductor, like steel for instance.

Lambda (λ): A conductance is given for each material and you cannot change it without changing the material, i.e. without compressing this material (increasing its conductance) or expanding this material (diminishing its conductance). A high conductance means that the heat travels quickly through the material, while a low conductance means that the material resists the passage of heat and is therefore insulating. The coefficient λ (lambda is a Greek letter which corresponds to our l) measures the conductance in W/m°C or in kCal/m h °C (1 W = 1.162 kCal/h) for each material and expresses the heat flow which is transferred:

- through a surface of 1 m^2 of this material,
- for a difference of temperature of 1 °C between its inner side and its exterior side,
- and for a thickness of 1m of homogeneous material.

E.g. we have the following conductances for the following materials:

- aluminium 230 W/m°C,
- steel 52 W/m°C,
- granite rock 3.0 W/m°C,
- concrete 1.75 W/m°C,
- brick 0.7 W/m°C,
- wood 0.23-0.29 W/m°C according to density,
- cork 0.044 W/m°C.

We can notice that in general the heaviest material is the most conductive because it is the densest, but it is not a regular rule; for instance aluminium is almost 3 times lighter than steel but more than 4 times more conductive.

Resistivity: The resistivity of a material to heat transfer is the opposite of its conductance: The resistivity is R = 1/λ. It is expressed in m°C/W, i.e. it expresses which surface of material must be exposed, and/or under which difference of temperature, for each m of thickness of this material to have an energy flow of only 1 W going through this material. Therefore heat resistance is the same kind of data like conductivity; it is related to the nature of the material and it cannot be changed.

Conductance of a material or conductivity of an element: Heat conductance and resistance are data which concern the quality of the material in use and cannot be changed. Nevertheless if you double the thickness of the element (e.g. the wall) made out of this material (e.g. brick), the heat flow will be reduce by half.

It is important to make the distinction between:

- the conductance of a material (brick or concrete or adobe) in W/m°C, which is not related to the dimensions of the building element (the wall), because it is a property of the material in use,
- and the conductivity of a given element (the wall) in W/°C which takes not only the quality of the material into consideration but also the measures of this element (its surface and its thickness).

The first concerns a general property of a given material and the second concerns a given part of the building with its own measurements. The quality of the second (the element or the wall) depends of course on the different qualities of the firsts (the different materials) but it depends also on the way to combine them and on the quantities of each of them.

Practical application: These data are very important because they allow us to measure how much heat gets lost and therefore how much heat must be produced or captured to replace it if we want to keep the same constant temperature inside.
You can calculate the loss - this is only valid for a simple element made out of a one material only:
$Q = A * \lambda/e * \Delta t$ where:

- Q is the flow of energy (in W),
- A is the surface of the element (in m^2) which is exposed to the difference of temperature,
- λ is the conductance of the material in W/m°C,
- e is the thickness of the element (in m),
- Δt is the difference of temperature between inside and outside.

This quantity of lost energy Q is the total flow of energy through the whole element but it does not take in consideration the duration of this flow. Therefore you have still to multiply the quantity of the flow (in W) by the duration (in h) to get the total energy loss (in J or kCal).

Example: If we have a 20 cm thick brick wall (e) with a vertical surface of 20 m^2 (A) exposed to a difference of temperature of 15 °C (Δt) between inside and outside, the loss of heat will be:
Q = 0.7 W/m°C * 20 m^2 * 15°C / 0.2 m = 1'050 W.
This is the energy flow through the wall (the 20 cm thick element with its 20 m^2 of brick) knowing that the brick (material) has a λ of 0.7 W/m°C. If this flow continues for 1 hour, the total quantity of energy will be 1.05 kWh, which is the quantity of energy to be replaced. We need to have this quantity of energy (in kWh, in J or in kCal) at disposal in our storage or we have to capture or to produce it. The question is how to return this heat at a speed which is sufficient to cover the loss, which is a flow in relation with time (in W).

3) The heat conductivity of a composed element

Composed element: A composed element is a building element made out of different layers of different materials. A wall can be made of 1 cm thick plasterboard (inside), of 10 cm of insulation and of 12 cm of brick (outside). The insulating capacity of each element participates to the total insulating capacity of the wall. It can be also calculated by using a different formula based no more on the λ but on the resistivity of each layer.

The coefficient k = coefficient of heat loss: it is the coefficient which gives the loss for each element, in W/m^2°C or in kCal/m^2h°C. It gives the energy flow of an element (wall, window, roof...) for each m^2 exposed and each °C of difference of temperature between inside and outside.

We have: k = 1/R where R is the total resistivity of the composed element. R = R1 + R2 + R3 + ... i.e. the sum of the respective resistances of the parts (layers) which are the e/λ of each layer. R = Σ of e/λ of each layer.

In fact, there are still two "invisible" layers which play an important role because of their resistivity to heat transfer through convection, i.e. the air layer on the interior side with its resistivity RI = 0.07 m^2°C/W and the air layer on the exterior side with its resistivity RE = 0.13 m^2°C/W. These quantities are invariable data for all cases.

We can therefore correct the formula: R = RI + R1 + R2 + R3 + ... + RE.

Example for the calculation of k for a composed element: Let us take the given example:

- resistivity of the plasterboard: λ for plaster = 0.35 W/m°C and e = 0.01 m.
  R1 (plasterboard) = 0.01m / 0.35 W/m°C = 0.03 m^2°C/W.
- resistivity of the insulation (glass wool): λ for glass wool = 0.035 W/m°C and e = 0.1 m.
  R2 (insulation) = 0.1m / 0.035 W/m°C = 3 m^2°C/W.
- resistivity of the brick wall: λ for brick = 0.7 W/m°C and e = 0.12 m.
  R3 (brick wall) = 0.12m / 0.7 W/m°C = 0.17 m^2°C/W.
- we have calculated the resistivity of each layer but we have still to include RI and RE.
- the total resistivity of the layers is R = RI + R1 + R2 + R3 + RE = 0.07 + 0.03 + 3 + 0.17 + 0.13 = 3.4 m^2°C/W.
- the coefficient k is: k = 1/R = 1W/3.4 m^2°C = 0.29 W/m^2°C. It means that each m^2 of the composed element will lose 0.29 W for each °C of difference.
- Thus a wall of this quality with a surface of 20 m^2 under a difference of temperature between inside and outside of Δt = 15 °C will lose: 0.29 W/m^2°C x 20 m^2 x 15 °C = 87W.
- The heating system will have to provide this energy at the same average rate as it is lost.

We can notice that the order of the layers has no influence on the calculation of the heat loss. It should not be like that; the system is in fact dynamic, because it varies from one hour to the next, and the fact to have the brick (thermal mass) inside or outside has an important significance which does not appear in our calculation. As the calculation is a simplified approach of the reality in a static system, it does not take the thermal mass into consideration.

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