Module 2, Lesson 1

The Heat Balance of the Human Body

Objective: How much energy does our body use? How do we keep cool when it is really hot out? Can we justify eating more when studying? The body maintains the power balance with the environment by eating, clothing and sweating. We will use the idea of a steady that we developed during our climate model to investigate the heat balance of the human body.

Introduction

Our model of the climate involved balancing the energy gathered from the Sun verses the energy radiated away. This is simply a balance of the energy intake of a system verses its energy output. We also considered the affect of an insulating layer, the atmosphere, on the temperature at the surface of the Earth. We will take these exact concepts and apply them to the heat balance of the human body.

Homeotherms (mammals, humans) regulate their internal body temperature within a range of about 1C despite large fluctuations in the temperature of their surroundings. This is achieved by balancing the flow of heat energy. We can divide the main components of this power balance in classic physicist's fashion (conduction, convection, radiation, evaporation) as follows [1]:

$$M + R = C + \lambda + G + S$$

Here *M* is the metabolic rate (generated internally by digesting food), *R* is the power absorbed in the form of radiation, *C* is the power lost by convection, λ is the power lost through the evaporation of sweat, *G* is the power lost through conduction and *S* is the power stored. Depending on circumstances *R*, *C*, *G* and *S* may have negative values. For this article, we will assume *S* is negligible compared to the other quantities (which is a healthy state for a mammal to be in): this is what we call "steady state". We will spent the next five sections investigating each term in this balance in detail.

1. Metabolic rate, *M*

In the human body, the rate of internal energy production is called the metabolic rate. As food is broken down, and glucose is oxidized, heat is released. This oxidation process can be written in chemist's fashion as follows [2]:

$$C_6H_{12}O_6 + 6O_2 \dashrightarrow 6H_2O + 6CO_2 + 686 \text{ kcal}$$

Recall that 1 food calorie = 1 kcal is approximately 4200 J and one mol of glucose is 180 g. So, for 1 gram of sugar, 16,000 J of energy is produced.

$$\left(\frac{686\ \text{kcal}}{180\ \text{g}}\right)\left(\frac{4200\ \text{J}}{1\ \text{kcal}}\right) = 16000\ \text{J}$$

So in physicist's terms, glucose generates 16 MJ/kg (strictly this is called the enthalpy of oxidation).

The Basal Metabolic Rate (BMR) or MB is the energy the body consumes when it is completely at rest (i.e. if you were lying in bed all day). It is the energy required to perform only critical body functions such as breathing and circulation.

$$M_B \propto m^n$$

where m is the mass of the body and the exponent n lies between 2/3 and 3/4. The heat from the basal metabolism is mainly dissipated through the skin, hence the basal rate is approximately proportional to the surface area of the animal (i.e. for animals of different size but the same shape, n = 2/3). The mean surface area of a human is approximately 1.7 m2 and a reasonable approximation for the BMR of a human is about 100 W (2000 kcal/d). Hence MB ≈ 60 W/m2 of body surface area. Any exercise on top of the BMR requires more power.

To maintain a steady flow of heat from the human body's core at 37 C to the environment, the skin has to have a temperature of about 33 C. A rise in M means various physical processes have to come into play to maintain the skin temperature, primarily the removal of clothing and sweating. We will not discuss here how the heat flows inside the body, only how it flows to and from the environment.

A person's weight is a balance between their caloric intake and their energy expenditure. Different foods (carbohydrates, proteins and fats) have different caloric values, or a different amount of energy in each gram [1]. If a person consumes less than they expend, they will lose weight, but if they consume more than they expend, they will gain weight. Any time you consume food you either use it, or your body stores it and you gain weight. When the body has used the energy from all of the consumed food, it then starts using up your energy stores. You need to balance how much food you eat with how much energy you use, or how active you are, and this article assumes these are balanced.

Movement

Different activities require different amounts of energy. The power used also depends on the weight of the person (heavier = more power for the same activity) and the intensity of the activity (more intense = more power). How would you rank the following activities: sleeping, swimming, running, walking, water aerobics, biking, and skating?

Check the table below to see if you were right (the ranges in numbers accounts for the intensity at which the exercise is done). Note: the following numbers were taken for a 65 kg female; a 90 kg male would burn about 1.5 times more calories doing the same exercise at the same intensity [3].

Activity	kcal/h
Sleeping	60
Walking (5 km/h)	280
Water Aerobics	300 - 500
Skating	300 - 600
Swimming	300 - 600
Running	400 - 700
Biking	450 - 700

Note that 1 kcal/h = (4184 J)/(3600 s) = 1.16 W, so the numbers in watts are only slightly higher than the numbers in kcal/h.

Thinking

What about thinking? After spending hours studying hard, do you feel especially hungry and reward your efforts with a tasty snack? What causes this increased hunger? How much more food can you justify eating?

In a recent study, participants were asked to spend 45 minutes sitting in a chair one day and 45 minutes reading an article and summarizing it another day. After they did these tasks, participants were given a survey on how hungry they were and then were given the chance to eat. It was found that when sitting in the chair, participants expended ~60 kcal and when they were reading and writing they expended 85 kcal. All participants indicated a similar level of hunger, but those who sat ate 900 kcal of food and those who studied ate 1150 kcal of food. The difference in the energy expenditure of sitting vs. studying was only 25 kcal, but the difference in the food consumed afterwards was 250 kcal [4,5]!

Activities requiring significant cognitive demand favour an overconsumption of food without increased feelings of hunger. Why? Thinking requires glucose. The body keeps some glucose in the bloodstream, but stores most of it as glycogen, which it has to convert back to glucose to use. While you are thinking, your brain quickly depletes the glucose stores in your blood, and tells you unconsciously to eat so that you can return the glucose levels to normal. This results in you eating more while you study, even though you don't necessarily feel hungry.

So, next time you are studying, try to resist the urge to constantly eat, or to eat a giant snack when you do decide to visit your kitchen. If you do give in, try rewarding a long day studying by taking a break and going for a bike ride!

2. Radiation, R

The total radiation power absorbed from the environment is R. We can further decompose this term into longwave radiation from the local environment (thermal infrared from buildings, the ground, flora, and the sky) and short wave radiation from direct sunlight (visible and near infrared):

$$R = R_L + R_S$$

You can read more on radiation in the article on Thermal Radiation.

The longwave radiation component can be calculated using the following formula:

$$R_L = A\epsilon\sigma(T_{skin}^4 - T_{env}^4)$$

where A is the surface area of the body, ε is the emissivity of skin (~0.98), σ is the Stefan-Boltzmann constant, T_{skin} is the (absolute) skin temperature (i.e. 306 K for bare skin) and T_{env} is the (absolute) temperature of the environment. A complication occurs when we consider clothing. Clothing reduces radiation loss by lowering our effective surface temperature. However, when clothed, different parts of our body will have different surface temperatures, and we should calculate RL separately for each. Note also that in many cases T_{env} is not uniform (see annotated photographs at the bottom of the Thermal Radiation article), making the application of this formula yet more complicated.

Figure 1. On a typical day, different amounts of heat are radiated from different objects in the same environment. The above pictures were taken with a normal camera (left) and an infrared camera (right) on a cool day in June. Objects emitting more radiation appear lighter and those emitting less radiation appear dark -- the people in this picture are much hotter than the environment and so stand out as being much lighter in colour in IR camera.

When your skin temperature is higher than the temperature of the environment, you radiate heat into the environment, but when it is lower, you absorb heat radiated from the environment. Short wave radiation, RS, coming from the Sun (up to ~ 1 kW/m^2 or more on a clear day on an area facing the Sun directly [6]).

Example: 54C in Baghdad

Question: The temperature in Baghdad, Iraq, hit 54C in August 2010. What does this do to the radiation balance of a human body? Let's assume you are inside, or under shelter such that the energy balance is between your body and the air. What are your radiative losses?

Answer: For T_{skin} = 306 K and T_{env} = 327 K, RL ≈ - 146 W to -438W given a surface area between 1 m^2 and 3 m^2. Notice the heat loss is negative, you've taken on heat!

On top of this, if one walks out into bright sunlight 1 kW/m^2, and estimating that the area of the body facing the Sun is 0.5 m^2 and that clothing or skin absorbs roughly 50% of the light, one can estimate the power absorbed from the Sun to be:

$$R_S = (0.5)(1000\ \mathrm{W/m}^2)(0.5\ \mathrm{m}^2) = 250\ \mathrm{W}$$

This is a big heating load to bear, but it gets worse, as we also need to consider convection, which is not going to cool us in these circumstances.

Figure 2. In the picture above, the surface temperature of the person's clothing is ~29^{o}C but the surface temperature of the concrete is 38^{o}C and so the person appears darker than the surroundings. Notice that the grass looks much cooler than the surroundings - this is due to evaporative cooling; the grass is quite damp, and thus the water molecules with a higher kinetic energy (and temperature) evaporate, leaving behind those with a lower kinetic energy, cooling the grass.

3. Convection, C

Convection is the transfer of heat by gas or liquid in motion (in our case, between our skin or clothing and the surrounding air). Once again, the heat transferred between the two is dependent on the temperature difference between them. There is also another important component to calculating the power transferred: the speed with which the air is moving. To a good approximation, and everything else being equal, convective losses (and gains) are proportional to area and temperature difference:

$$C \approx K_C A(T_{skin} - T_{env})$$

where A is the surface area of the body, T_{skin} is the skin temperature, T_{env} is the temperature of the environment and K_C is an empirical factor that applies to the geometry of the human body. It varies as the speed of the air varies [1]:

Speed of air	K_C
0 m/s	3 $W/m^2/K$
2 m/s	26 $W/m^2/K$
10 m/s	37 $W/m^2/K$
10 m/s	41 $W/m^2/K$

We see that K_C is dependent on the speed of moving air, and thus the power transferred is going to change with a change in the air speed. Note that the largest difference is between the still and slow-moving air, and not so much between higher speeds. For a temperature difference of 5 K, the power transferred through convection with still air is only 20 W, whereas if the air is moving at just 2 m/s, the power transferred is 200 W.

The reason our bodies cool down when wind blows is due to a combined effect of the temperature and wind, known as wind chill -- if you have taken a walk on a cold day, you probably felt colder when the wind blew. Our bodies create a form of its own insulation on known as the boundary layer, by warming up a thin layer of air close to the skin. As the wind blows, it takes this protective layer away, and our bodies use energy to warm up a new layer to prevent our skin from being exposed to the outside air. Thus if each layer keeps getting blown away, our skin temperature drops and we feel colder [7]. A wind speed of 2 m/s is just enough to blow away the stagnant boundary layer of air around the body and replace with fresh air from the environment.

A variant of convective loss is the power we lose to our breath. We can estimate this from our breathing rate (typically 6 L/min) and the heat capacity of air (1.3 J/K/L). For a core (breath) temperature of 37 C and an ambient temperature of 20 C, this component of convective loss works out to be a mere 2.2 W. This number rises to about 16 W if we consider the moisture loss in breathing [1] (see next section).

Example: 54C in Baghdad

Question: But what about in Baghdad? If the environment is 5 C cooler than our surface temperature, we lose 20 W, but what if the environment is 21 C hotter than our skin temperature and there's a 5 m/s breeze?

Answer: Our heat loss is between -588 W and -2200 W from convection, which means we're gaining heat! Not much a a breeze. On top of it, the heat gain is getting extreme, but there's a way out, just.

4. Evaporative loss, λ

The latent heat of a substance is the amount of energy released or absorbed during a change of state, with no change in temperature. The latent heat of vaporization of water is thus the energy absorbed as water changes from a liquid to a gas. At at 30 ^{o}C, it is approximately 2.4 MJ/L.

Sweating is a primary mechanism that our body uses to cool us; on a hot day, we sweat and the sweat evaporates off our skin, cooling us. The energy to evaporate our sweat, the latent heat of vaporization, is provided by our bodies. This evaporation in turn cools our bodies. However, being wet in the winter can also chill us because of the same evaporation effect. Do you think we would still keep cool if the sweat dripped off our bodies instead of evaporating?

We can sweat a maximum of 1-1.5 L/h. Given that 24 MJ is lost in the evaporation of 1 L of water/sweat (for now we approximate them as the same), we can find the power loss due to this evaporation:

$$\lambda \approx (\frac{2.4\text{MJ}}{\text{L}})(\frac{1.5\ \text{L}}{\text{h}})(\frac{1\ \text{h}}{3600\ \text{s}}) \approx 1000\ \text{W}$$

The environmental humidity level plays a big role in our ability to sweat. If the air is dry and there is no humidity, there is no barrier to how much we can sweat. We never have zero absolute humidity - the closest it ever gets is 0.03 % in Antarctica [8], where the water is too cold to hold any water. Fortunately, our bodies won't usually perspire in Antarctica, otherwise with no barrier to sweating, we would probably get dehydrated fairly quickly! On the other hand, the higher the humidity, the more difficult it is for our sweat to evaporate. Thus on hot humid days, we feel more uncomfortable than on hot dry days [9]. This also explains why we use a fan, even when it is very hot and the moving air increases our convective heating: the fan blows away the boundary layer of air saturated with water, and allows us to continuing evaporating sweat.

Without visible sweating, our total evaporative loss (including breathing) is 25% - 30% of our metabolic rate. This is approximately 30 W or 50 mL/h of water.

Example: 54C in Baghdad

Fortunately when the mercury hit 54 C, the relative humidity was less than 20%, so evaporative cooling (plus a lot of acclimatization) could cope.

5. Conduction, G

Conduction is the transfer of heat from high temperature to low temperature by direct contact between solid materials. As we have been considering heat loss from the exterior of the body and clothing, the only solid contact when standing is through shoes, or if seated, whatever one is sitting on. For shoes, the conduction rate is dependent on the temperature difference between the skin and the floor, and the thermal properties of the sole material [10].

Conduction losses are found using the following formula:

$$G = \frac{kA(T_{skin} - T_{env})}{d}$$

Where G is the conduction loss in W, k is the thermal conductivity (measured in W/(m K), Watts per metre per Kelvin), d is the thickness of the material (in m), T_{skin} is the temperature of the skin and T_{env} is the temperature of the environment. Since we are only require the temperature difference, we could use either K (kelvin) or ^{o}C (degrees celsius).

Example: flip-flops

Question: A good example would be to consider conduction losses from our feet: what would be our conduction losses from our feet if we are wearing rubber flip flops?

For a rubber (polyurethane) flip flop:

$$\begin{aligned} A &= (30\ \text{cm})(20\ \text{cm}) = 0.06\ \text{m}^2 \\ k &= 0.02\text{W}/\text{mK} \\ d &= 1\ \text{cm} = 0.01\ \text{m} \\ T_{skin} &= 306\ \text{K} \\ T_{material} &= 293\ \text{K} \end{aligned}$$

Answer: Thus, the conduction per foot is found as:

$$\begin{aligned} G &= \frac{(0.02)(0.06)(306-293)}{0.01} \\ &= 1.56\ \text{W} \end{aligned}$$

A total loss of 3.12 W (1.56 W/foot * 2 feet) is small, much smaller than that of all the other processes considered.

Conduction losses, however, aren't always so small: misbehaving prisoners in the famous Alcatraz prison in San Francisco Bay were stripped of their clothes thrown into "The Hole" for punishment. "The Hole" was an enclosed prison cell that had no windows or doors and was made of concrete - the room was never heated. Concrete has a fairly high thermal conductivity (0.29 - 1.73 W/mK) [11] and so if the prisoners lay down on the floor, their large surface area and large thickness, together with the high K_C meant that conduction losses were very high - between 80 W - 400 W during 0°C weather. To prevent these losses (and their bodies consequently freezing), the prisoners would prop themselves off the ground by resting their elbows and knees on toilet paper rolls. The reduced surface area in contact with the material and the low conductivity of paper (0.05 W/mK) lowered their conduction losses by a substantial amount, at the expense of an uncomfortable posture.

Summary

We've considered many aspects of how the body regulates its temperature, even in extreme environments.

Resources

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