3.9.1: Biology- Anaerobic Fermentation in Beer and Lactic Acid in Muscles

Pasteur showed that sugar fermentation in the presence of oxygen (*aerobic fermentation*) leads to a maximum rate of yeast growth, but minimum alcohol production. Excluding air (so the process continues *anaerobically*) slows yeast growth, but increases alcohol production. Anaerobic processes usually produce less energy than aerobic ones. We notice the same thing in our muscles when all the blood oxygen is used up, and lactic acid is produced (see below).
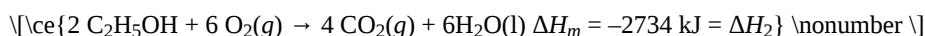

Fermentation product

Let's see how thermochemical equations help explain the "Pasteur Effect" and energy associated with lactic acid buildup. In case you're wondering, the heat energy values below can be obtained from the National Institute of Standars and Technology website NIST, from the home page use a **name** search for "ethanol".

Perhaps the most useful feature of thermochemical equations is that they can be combined to determine ΔH_m values for other chemical reactions. Consider, for example, the following two-step sequence. Step 1 is anaerobic fermentation of glucose, $C_6H_{12}O_6$, to make 2 mol of ethanol, C_2H_5OH and 2 mol $CO_2(g)$:

\[\ce{C6H12O6(l) → 2 C2H5OH(l) + 2 CO2(g) ΔH_m = –74.4 kJ = ΔH_1} \nonumber \]
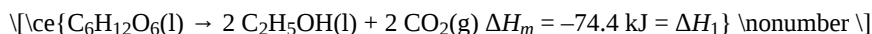
Note that a small amount of energy is produced anaerobically. \

If oxygen becomes available, the C_2H_5OH reacts with 6 mol O_2 yielding 4 mol CO_2:

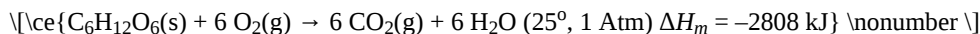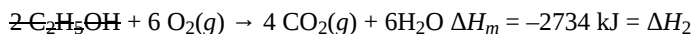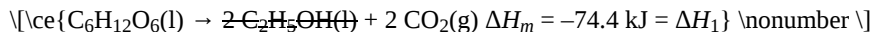\[\ce{2 C2H5OH + 6 O2(g) → 4 CO2(g) + 6H2O(l) ΔH_m = –2734 kJ = ΔH_2} \nonumber \]

The net result of this two-step process is production of 6 mol CO_2 from the original 1 mol $C_6H_{12}O_6$ and 6 mol O_2. All the ethanol produced in step 1 is used up in step 2. The overall effect is the same as the aerobic fermentation of glucose:

\[\ce{C6H12O6(s) + 6 O2(g) → 6 CO2(g) + 6 H2O (25°, 1 Atm) ΔH_m = –2808 kJ} \nonumber \]
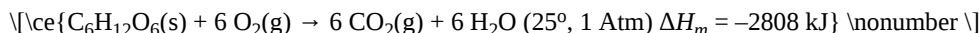
Now we see an explanation for the "Pasteur Effect". If yeast grows in air, it can produce 2808 kJ/mol sugar, just like we do. That's energy that can be used to synthesize compounds and grow (we could use it to move around, but yeast can't do that!). If yeast ferments the sugar anaerobically, it can only produce 74 kJ/mol sugar, so growth is retarded, but it produces a lot of alcohol! The difference is the energy that comes from the aerobic metabolism of alcohol, producing 2734 kJ (for 2 mol ethanol).
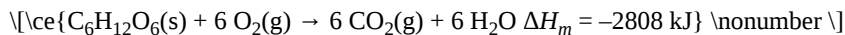
On paper this net result can be obtained by *adding* the two chemical equations as though they were algebraic equations. The ethanol produced is canceled by the CO consumed since it is both a reactant and a product of the overall reaction

\[\ce{C6H12O6(l) → ~~2 C2H5OH(l)~~ + 2 CO2(g) ΔH_m = –74.4 kJ = ΔH_1} \nonumber \]

~~2 C2H5OH~~ + 6 O$_2$(*g*) → 4 CO$_2$(*g*) + 6H$_2$O ΔH$_m$ = –2734 kJ = ΔH$_2$

\[\ce{C6H12O6(s) + 6 O2(g) → 6 CO2(g) + 6 H2O (25°, 1 Atm) ΔH_m = –2808 kJ} \nonumber \]

Experimentally it is found that the enthalpy change for the net reaction is the *sum* of the enthalpy changes for steps 1 and 2:

ΔH_{net} = –74.4 kJ + (–2734 kJ) + –2808 kJ = ΔH$_1$ + ΔH$_2$} \nonumber \]

That is, the thermochemical equation

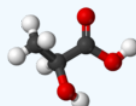\[\ce{C6H12O6(s) + 6 O2(g) → 6 CO2(g) + 6 H2O ΔH_m = –2808 kJ} \nonumber \]

is the correct one for the overall reaction. Note that this is the same equation, and same heat of reaction, that we used [Weight of Food and Energy Production |before].

In the general case it is always true that *whenever two or more chemical equations can be added algebraically to give a net reaction, their enthalpy changes may also be added to give the enthalpy change of the net reaction.*

This principle is known as **Hess' law**. If it were not true, it would be possible to think up a series of reactions in which energy would be created but which would end up with exactly the same substances we started with. This would contradict the law of conservation of energy. Hess' law enables us to obtain ΔH_m values for reactions which cannot be carried out experimentally, as the next example shows.

> ✔ Example 3.9.1.1:
>
> During exercise, glucose is first metabolized according to equation (1) above because there is plenty of oxygenated blood around muscle tissue. But as the oxygen is depleted, glucose is metabolized anaerobically to lactate ion to produce energy (we'll simplify by showing it as solid lactic acid):
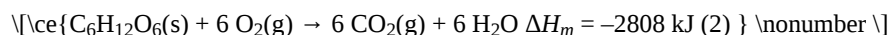>
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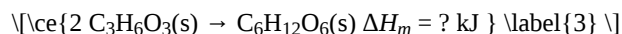> Lactic acid

When blood once more supplies oxygen to the muscle, the lactic acid is metabolized according to the equation below:

$$\ce{C3H6O3(s) + 3 O2(g) -> 3 CO2(g) + 3 H2O (l)} \Delta H_m = -1344 \text{ kJ} \quad (1)$$
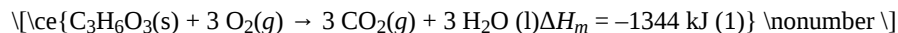
Use ΔH_m for this reaction, and for the aerobic metabolism of glucose:

$$\ce{C6H12O6(s) + 6 O2(g) -> 6 CO2(g) + 6 H2O} \quad \Delta H_m = -2808 \text{ kJ} \quad (2)$$

to calculate ΔH_m for the reaction,

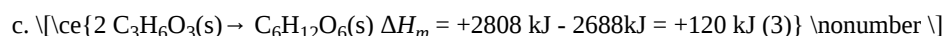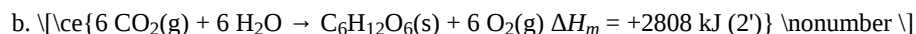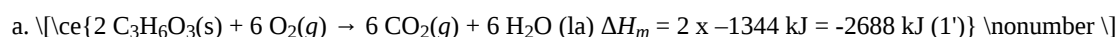$$\ce{2 C3H6O3(s) -> C6H12O6(s)} \quad \Delta H_m = ? \text{ kJ} \quad (3)$$

Solution

We use the following strategy to manipulate the three experimental equations so that when added they yield Eq. (1):

a) Since Eq. (3) has 2 mol $C_3H_6O_3(s)$ on the left, we multiply Eq. (1) by 2. We also double the heat energy produced.

b) Since Eq. (3) no H_2O or CO_2, we need to cancel these molecules. Since Eq. (1) has *6* mol CO_2 and 6 mol H_2O on the *right*, whereas there also CO_2 and H_2O on the *right* of Eq. (2), we write Eq. (2) in reverse so they'll cancel. We also change the sign on the heat energy, indicating that it is absorbed rather than released.

c) Reversing (2) also puts $C_6H_{12}O_6(s)$ on the right in (2'), where it appears in (3), so we can combine the equations, cancelling molecules that appear on both sides.

We then have

a. $$\ce{2 C3H6O3(s) + 6 O2(g) -> 6 CO2(g) + 6 H2O (la)} \quad \Delta H_m = 2 \times -1344 \text{ kJ} = -2688 \text{ kJ} \quad (1')$$

b. $$\ce{6 CO2(g) + 6 H2O -> C6H12O6(s) + 6 O2(g)} \quad \Delta H_m = +2808 \text{ kJ} \quad (2')$$

c. $$\ce{2 C3H6O3(s) -> C6H12O6(s)} \quad \Delta H_m = +2808 \text{ kJ} - 2688 \text{kJ} = +120 \text{ kJ} \quad (3)$$

The result (3) is interesting; in reverse, it's $C_6H_{12}O_6(s) \rightarrow 2 C_3H_6O_3(s)$ $\Delta H_m = -120$ kJ (3)

which is the amount of energy from anaerobic conversion of glucose to lactic acid. We can see that it isn't much, but the reaction proceeds rapidly again and again, producing significant amounts of energy. The alternative would be no energy at all in the absence of oxygen.

Since lactic acid is normally metabolized as soon as oxygen is again available, it isn't the cause of "day after" muscle ache, as people erroneously say. It's actually the cause of burning muscles that you feel during exercise. But even then, it's an indirect effect; the lactic acid itself doesn't cause the burning, but causes formation of a flood of ATP, which hydrolyzes to give the acid which causes the |pain

References

1. Campbell, J.A., J. Chem. Educ. (1973), 50, 563

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