IB01x - 4.5 - Heat transport

Before, we have had a look at limiting transport steps of oxygen and carbon dioxide. In this unit we will discuss another transport factor that can limit the overall rate of the reaction in large scale fermenters: heat removal. I believe a very cool topic that you will like.

In aerobic fermentation processes, and to a lesser extent in anaerobic fermentation processes, a lot of heat is produced. This can be easily in the order of megawatts; heat that has to be removed. The cooling water that is used to shuttle these megawatts out of the fermenter is usually not so much different in temperature compared to the broth. The driving force for temperature transfer can be as low as 20 or even 10 degrees, and therefore a good heat transfer design is needed. In this unit, we will discuss different heat sources and sinks in the bioreactor.

Considering a bioreactor: what are the terms that make up the heat balance? The process reaction is the first and largest contributor; it can be viewed as a combustion: oxygen is needed to ‘burn’ the glucose. There is an easy rule-of-thumb to calculate this amount: for each mole of oxygen consumed there is 450 kJ of heat produced. For anaerobic processes usually this is a factor 10 lower, but because anaerobic fermentations are often carried out at a larger scale, with less area per volume available for cooling, cooling strategies are equally important. In stirred tank reactors, the second most important term of heat production is the impeller . Energy dissipation via the impellers can add another 10-30% of heat on top of the reaction heat. The advantage of the bubble column and the airlift loop reactor is clear, because then you don’t have the impeller. There can be other sources of heat as well , such as hot feed streams or hot gases that are introduced in the broth. An important sink of heat is evaporation; water has a high heat of vaporization and therefore water evaporation can have an extra cooling effect. The cumulative heat generated needs to be transferred away from the fermenter. This can be done in various ways, for example via coils, the vessel wall, baffles or via an external loop with a heat exchanger through which the heat is transferred to cooling water.

We will have a look at the cooling coils first, mounted either as a long spiral inside the reactor , or welded as half-pipes at the outside wall.

A series of steps is required to transport heat from the broth via the coils to the cooling water. First, there is a convective flow of heat from the bulk of the liquid to the coil. Secondly, there is a transfer through a liquid film outside the coil, conduction through the coil material, and transfer through a liquid film at the cooling water side, and third there is convective flow away from the system via the cooling water.

There are two central terms, that are used to quantify heat transfer. First is the heat transfer coefficient, U, which applies to the area across which heat is transferred. The second is the heat capacity of the cooling fluid, ρ times c_p.

You might wonder whether there are temperature gradients in the bulk of the broth in large fermenters. This is not the case – it can safely be assumed that the bulk temperature inside a properly mixed fermenter is everywhere the same.

What is the relation between heat transfer through the coil and convection in the cooling water? Let us consider the transfer process in more detail. Cold water flows in, and absorbs heat that is supplied through the wall of the coil. Under steady state conditions, the energy balance set up over a small section of the coil shows that convection and transfer are equal.

The Stanton number is an important quantity in the design of a cooling system. It is a dimensionless number that indicates the ratio of the transfer and convective capacities. In an ideal situation, the Stanton number should be close to 1. If it is much lower than 1 then you have an overcapacity of the cooling water flow, meaning that the temperature of the cooling water at inflow is equal to its temperature at outflow. If the Stanton number is much higher, say about 10, then the opposite is true and the outlet temperature of the cooling water is equal to the temperature inside the fermenter. This happens when cooling area is too large compared to the flow of cooling liquid, for example when the coil is too long. For very large fermenters, the available cooling area per volume, which equals 4 divided by the tank diameter, will become too small for adequate cooling, and an external cooling loop needs to be installed for cooling.

The great advantage of external cooling is that you have greater design freedom, meaning that more heat can be transferred. Using a cooling coil may result in a few degrees lower temperature in the thin liquid film on the broth side. In comparison, the external loop can easily generate 5 degrees of cooling for all broth elements every 10 or 20 minutes.

External cooling loops also present challenges. The microorganisms have to be capable of handling the cold shocks, which are more severe than with cooling coils. Also, there is a relatively high shear rate in the transport pump, which can cause damage to the microorganisms. Another disadvantage is that you need a special type of pump that will prevent contamination, which requires a good capital investment as well as extra costs for electricity and maintenance.

The cooling requirement of the PDO process is approximately 51000 kJ/s , as was calculated in week 3. From this value we can calculate all the key design elements, including the required flow rate through the cooling loop.

Assuming a temperature difference of 5 degrees over the loop, then a cooling water flow of 2.46 m^3/s is needed. On average, the organisms pass the loop every 15 minutes, although some cells may pass more frequently, and others only incidentally.

Finally, a good design is essential for sufficient cooling at minimum costs. In large reactors, the total heat production rate can be high and requires a heavy duty cooling system to keep the temperature in the fermentation at the desired value. Evaporation can be a useful heat sink to reduce the cooling need, and you should not forget heat that is produced via the impeller in stirred tanks. There can be hot spots in your large scale reactor, for example close to the inlet points of hot gas or hot feed liquid, and together with cold spots in the external cooling loops this can have a serious impact on the performance of the microbes. One example is that if the cells have a temperature-sensitive switch for making the desired product, then you should take care that product formation stays at level. In addition, long residence times in the loop can result in oxygen and substrate starvation, and this should be avoided with a proper design.

That completes the heat transfer unit. I hope you keep it cool!