Bioreactor Design and Analysis
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Lecture – 28
Heat Transfer Operations in Bioreactors – Part 1

Welcome back students. So today we are going to start with a new topic. This will be heat transfer operations in bioreactors. So, let us see what are the different heat transfer operations which are carried out during the fermentation processes in reactors?

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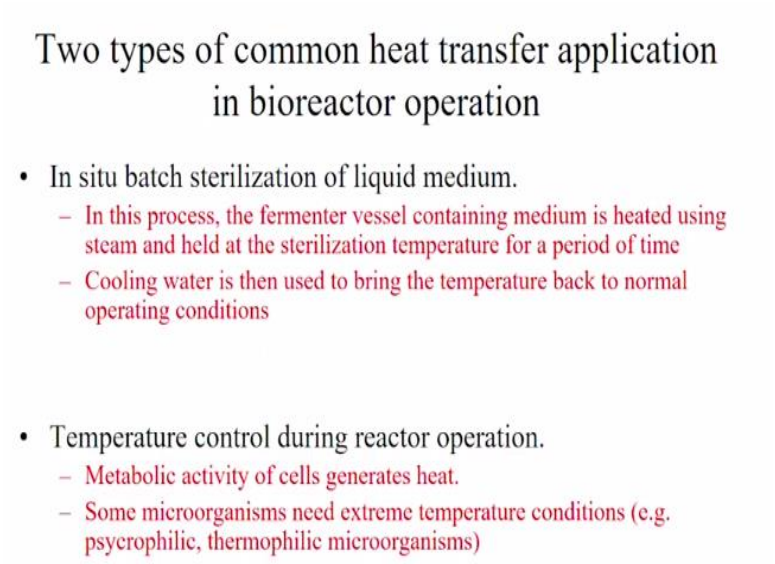

So, the two most common types of heat transfer applications in bioreactor operations include the sterilization process which is generally the in-situ batch sterilization of the liquid medium. Now in this process, the fermenter vessel containing the medium is heated using generally steam and then it is held at the sterilization temperature for a given period of time. And the cooling water is then circulated after sterilization to bring down the temperature back to the conditions required for the fermentations or the operating condition.

The temperature controlled during the reactor operation, this is important because it governs the metabolic activity of the cells which in turn they generate heat due to the metabolism. So, there will be heat generated by the growth of the cells then some of the microorganisms as per their natural coexistence and their natural characteristic they might be needing extreme temperatures for survival.

So, microorganisms are classified depending on the temperatures they require or at the temperatures at which they survive like psychrophilic, thermophilic or mesophilic organisms.

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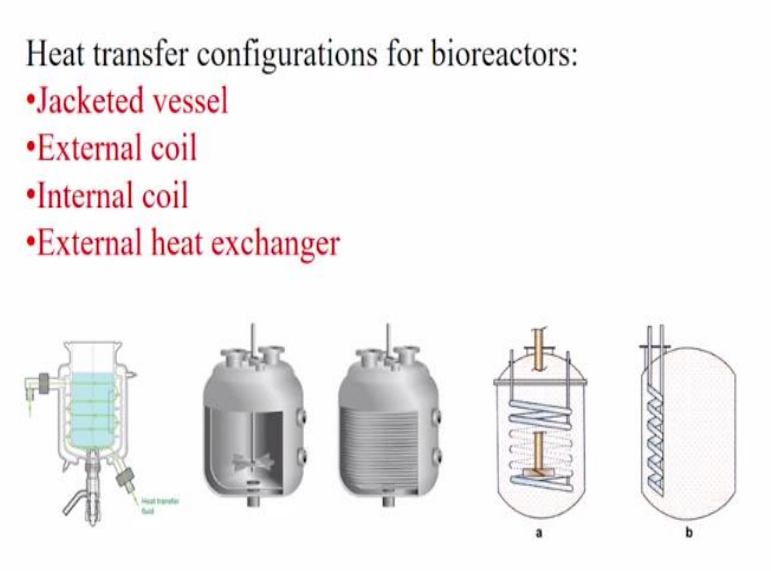

Then for sterilization one may come across especially in lab scale reactors you may come across jacketed vessels, then with increase in the size of the reactors there can be external coils wound around the reactor. If the size is very small of the lab scale reactor you may also see that there are heating and cooling fingers given inside the reactor and or if it is a very large scale industrial setup, then sometimes sterilization is done in a separate unit.

Which may be a heat exchanger connected to the fermentation medium. So, the fermentation medium is taken out, is passed through the heat exchanger unit for the sterilization process and then the sterile medium is circulated back to the reactor. Similarly, the control of the temperature is also done by the similar process.

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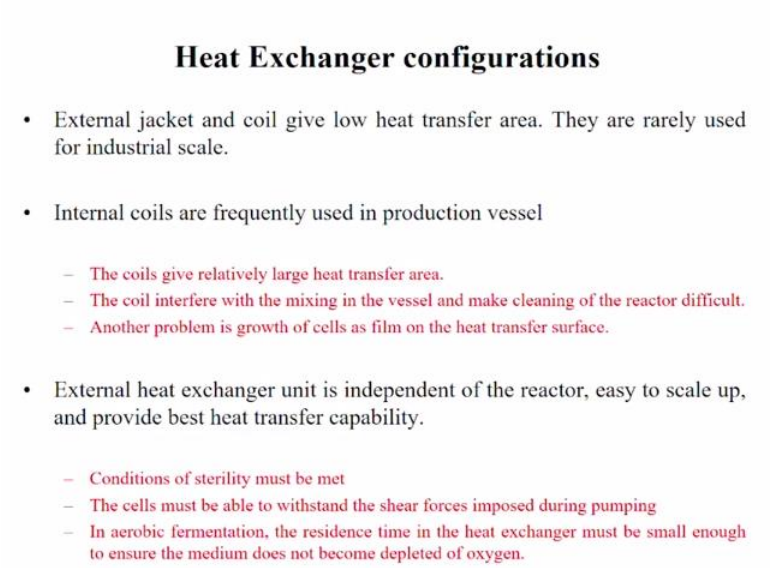

Now heat exchanger configurations; you may have external jacket and coil which sometimes may provide low heat transfer area. So, they are rarely used at large scale or industrial scale. Internal coils they are frequently used in production vessels where the coils they give relatively large heat transfer area. The demerit is that they may interfere with the mixing in the vessel and may also make the cleaning of the reactor difficult.

Another problem can be that the cell mass can get stuck to these coils and may start growing as films causing heat transfer and mass transfer limitations. Now external heat exchanger unit this is independent of the reactor as I mentioned. It is therefore easy to scale up and this can provide the best heat transfer capabilities. However, the points which have to be considered include that the conditions of sterility have to be maintained because now the fermentation medium is going outside the reactor.

The cells they should be able to withstand the shear forces which may be induced during the pumping operations to send the fermentation medium or to circulate the fermentation medium through the heat exchanger unit and bringing it back to the reactor. Especially in aerobic fermentations the residence time in the heat exchanger it should be kept as small as possible just to ensure that the medium does not become depleted of oxygen during this cooling process or heating process.

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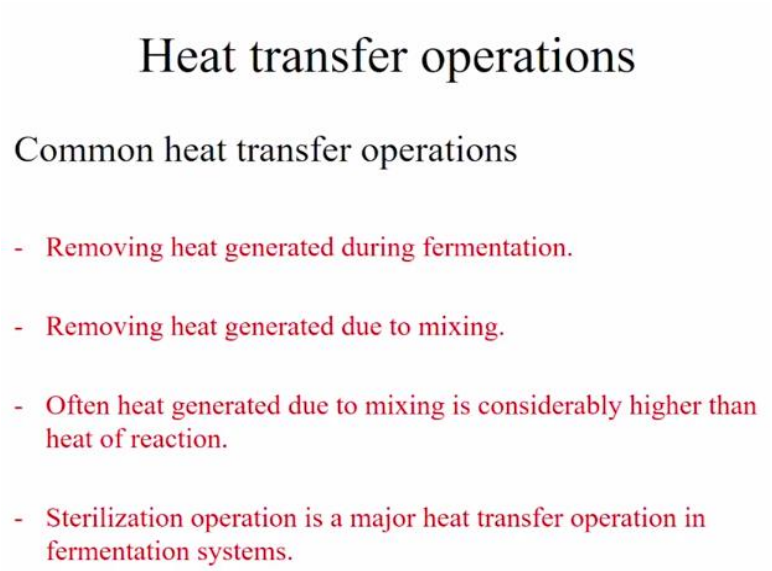

So, the common heat transfer operations they include the removal of heat generated during fermentation, removing the heat generated due to mixing especially in stirred bioreactors. Often the heat generated due to mixing this is considerably high than the heat of reaction which is your metabolic heat. Now the sterilization operation this forms the major heat transfer operation in the fermentation system.

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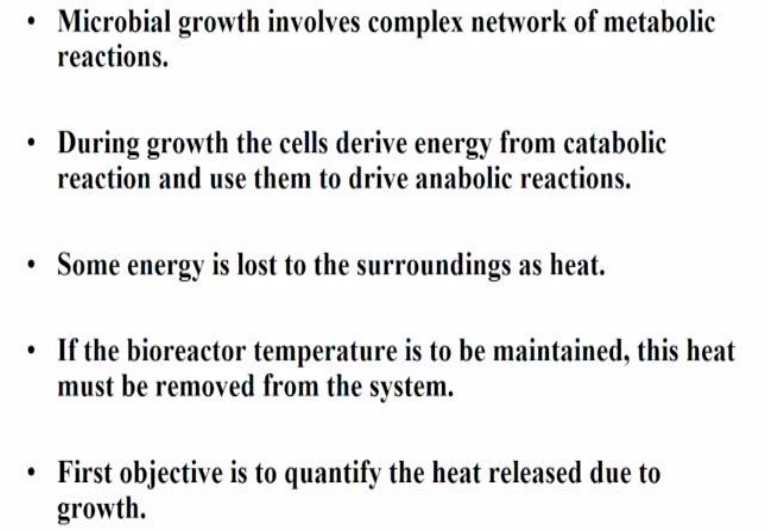

Let us characterize some of these heat transfer operations which are known to happen in any generalized fermentation process. So microbial growth, this involves complex network of metabolic reactions. Now during the growth of the cells, they derive energy from the catabolic reactions and they use them to drive the anabolic reactions. Now some of this energy during this process is lost to the surroundings as heat.

Now if the bioreactor temperature is to be maintained at an optimum value, then this heat must be removed from the system. So, the objective is to first let us quantify the heat which is released due to the growth of the biomass which we may term as the metabolic heat.

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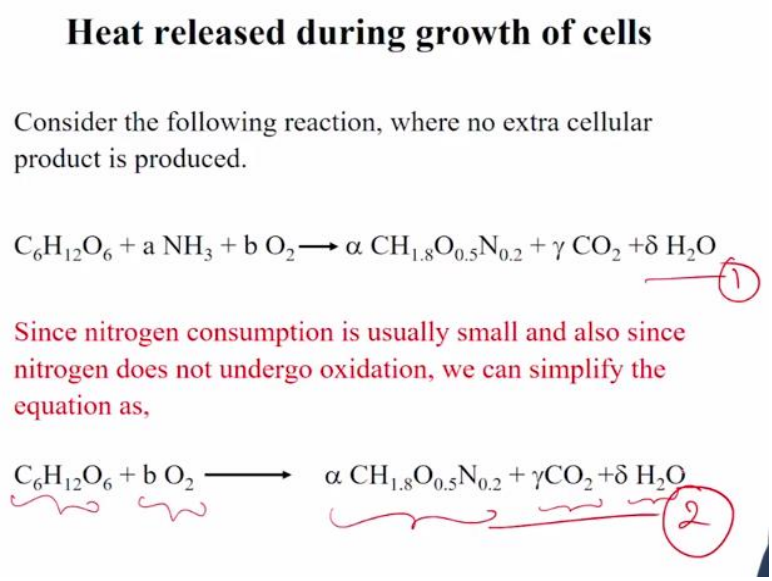

So, for that it will be nice to know the stoichiometry. Now consider the following reactions as shown on the slide. So, we are assuming there is no extracellular product formation. So, the carbon source, the nitrogen and the oxygen. The carbon source is oxidized to give the biomass and the waste products which are released are in the form of carbon dioxide and water.

Now since nitrogen consumption this is usually small, so we can neglect the nitrogen from the reactants and the nitrogen we know it does not undergo oxidation. So, we can simplify the first equation shown here in terms of the second equation where first term is your carbon source, glucose given here which is oxidized and then it gives the biomass. So, this is the molecular formula for biomass especially this is for bacteria, microbes and then these are the products of fermentation, the CO 2 and water vapor.

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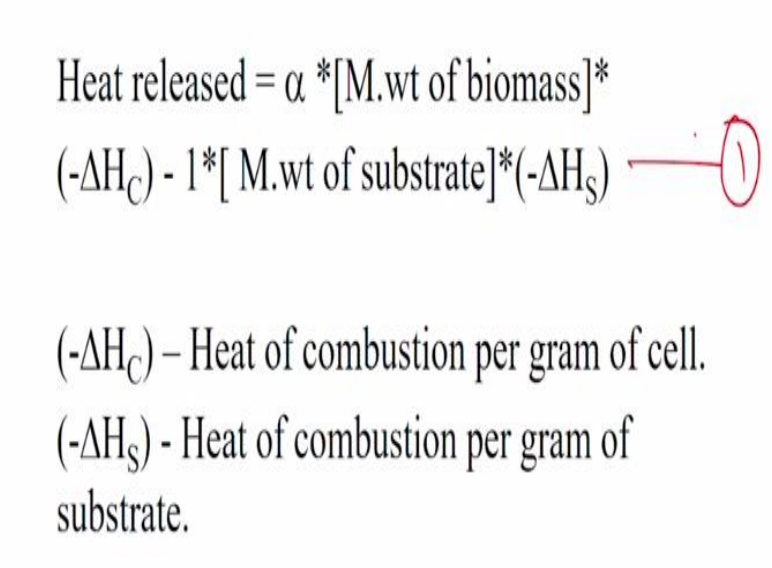

Now in order to find the heat released this would be what if we go by this equation 2? This will be alpha times the molecular weight of the biomass multiplied by the enthalpy of the heat of combustion of the biomass. So, we are doing it for the one mole of glucose consumed minus the molecular weight of substrate multiplied by the heat of combustion of the substrate.

So, this will give us this difference will give us the amount of heat released during the biomass formation. So, as I said delta H c is nothing but your heat of combustion per gram of cell. So, therefore it is being multiplied by the amount of biomass where alpha moles of biomass are known to produce to get produced so we will multiply alpha by the molecular weight of biomass. Similarly, delta H s this is heat of combustion per gram of substrate.

So, in this reaction equation 2 the total amount of heat which will be consumed during the oxidation of the substrate will be giving as the heat of combustion multiplied by the total amount of substrate consumed in the reaction. So because there is 1 mole of substrate consumed, so we multiply it by the molecular weight of the substrat,e.

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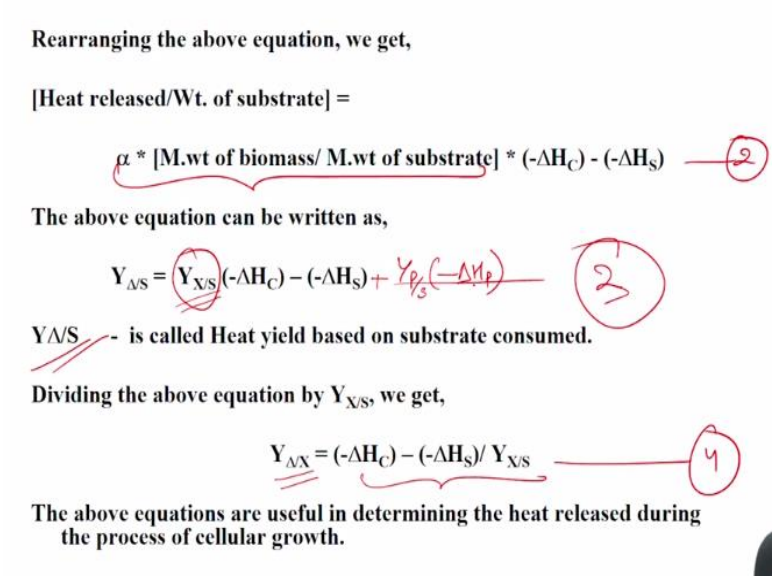

Now this heat released if we want to find with respect to the unit biomass, then we will divide it by the total amount of or if suppose now the heat released we need to find the yield coefficient which means the amount of heat released per unit substrate consumed. So then for that we will divide the entire equation by the total amount of substrate consumed here. So, this is nothing but the molecular weight of substrate because it is only one mole of substrate.

So, you can divide the entire equation given here, let us call it as equation 1, by the molecular weight of substrate. So, then the equation 1 becomes equation 2. So now if you see the amount of biomass to amount of substrate consumed is nothing but the Y x by s, is not it? Which is alpha times molecular weight of biomass 2 divided by the molecular weight of substrate because it is only one mole of substrates getting consumed.

So, then we have replaced this which I am showing by a curly bracket by Y x by s in equation 3 here. So, this Y delta divided by S this factor is called as the heat yield based on the substrate consumed. Now if we divide equation 3 by Y x by s, then we will get heat yield per unit biomass produced and the equation will be rearranged as shown in equation 4. Now this can be useful in determining the heat released during the process of cellular growth.

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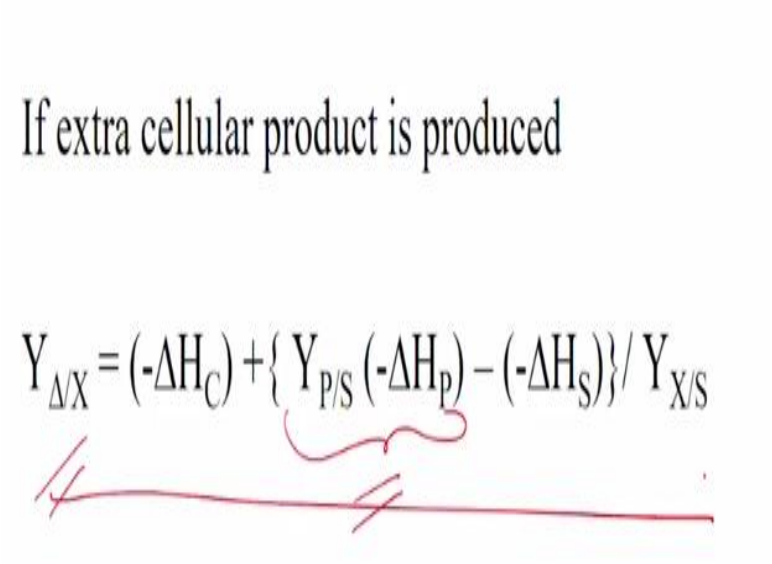

Now suppose there is extracellular product also getting formed, then the previous equation, equation 4 can be rewritten having the product yield also then the heat released per unit biomass consumed will also have the heat of combustion of the product multiplied by the yield of product per unit substrate consumed. And this will be the total amount of the product produced divided by the amount of substrate consumed as we did earlier to get equation 3 here.

So, we will have an extra term of Y p by s multiplied by minus delta H p which is being shown here by the curly bracket. So, what I meant was we will have an extra term here of Y p by s multiplied by delta H p and then the entire equation when divided by y x by s will give us this equation.

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Heat of Combustion of Biomass

(kJ g-1)

E. coli	-	**23.03**
E. cloacae	-	**22.83**
B. thuringiensis	-	**22.08**
Candida lipolytica	-	**21.34**
Candida boidinii	-	**20.14**
Kluyveromyces fragilis	-	**21.66**
Heat of combustion of Glucose	-	**15.60**

So just to give you some idea about the different heat of combustions of different microbial species, so they are listed down here.

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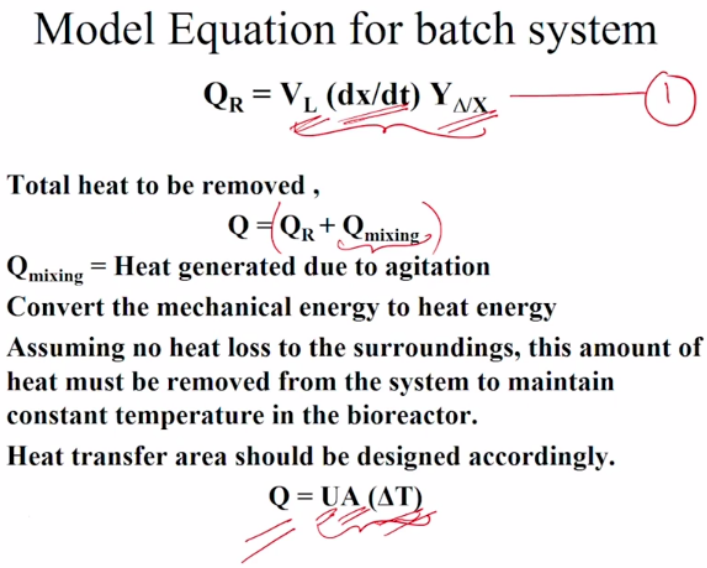

Now if we have to design a cooling system to maintain the temperature of the fermenter or the fermentation process at the required temperature, then the amount of heat which is released due to cellular growth and the amount of heat which is generated by the moving parts inside the reactor especially like impellers all this heat has to be transferred. So first we need to understand what is that total amount of heat which will be generated and which needs to be removed during the fermentation process.

So, in order to design the cooling system Q R would stand for the rate of metabolic heat which is generated or the rate at which the heat is generated due to growth rate of the culture. So, to determine that we will use equation 1 here once we know from the stoichiometry the heat yield per unit biomass and the growth rate of the culture. V L stands here for the volume of the batch system or due to agitation, the heat generated due to agitation is Q mixing.

Now in order to convert this mechanical energy to heat energy, assume no heat loss to the surroundings, this amount of heat must be removed from the system to maintain constant temperature in the reactor. So, now this total heat which is being generated this heat generated has to be removed. So, the cooling system we need to determine what should be the driving force? Which means which coolant at what temperature it should be run?

So, which means it is dependent on the temperature difference between the coolant and the fermentation medium, the surface area of the heat exchanging device and this is the total heat transfer coefficient, the overall heat transfer coefficient. Why overall heat transfer coefficient? I hope you can make out that there is convection and conduction through the wall of the fermenter and then again heat transfer from the surface to the bulk of the coolant medium.

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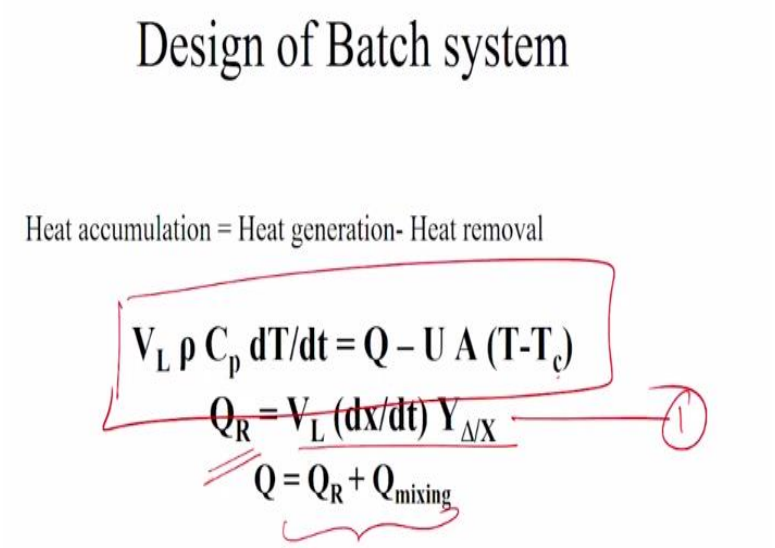

So, in order to design the batch heat exchanger, the amount of heat accumulated if you do a heat balance will be equal to the amount of heat generated minus heat removed. So, the rate at which the heat will be accumulated and the change in the temperature with time will be observed in the fermentation medium can be given as let us assume the rate of change of temperature with time is dT by dt.

C p is your specific heat, rho is the density of the fermentation medium, V L is the volume of the fermentation medium. So, m C p delta T is the rate at which the heat is getting accumulated in the fermentation medium. Now heat generated is the total Q which we just saw in the previous slide this one due to the mixing and due to the metabolic reaction. Heat removed depending on the driving force.

So, T is the temperature of the fermentation medium and T c is the temperature of the coolant, A is the heat transfer area or heat exchange area and U is the overall heat transfer coefficient. So, then this is the mass balance for the heat. So, your heat of reaction we know

can be given as shown here in this equation. So, your total amount of heat which is to be removed or which is generated is Q R + Q mixing.

So, this is the equation which governs the rate at which the temperature is going to change during the fermentation process in the medium.

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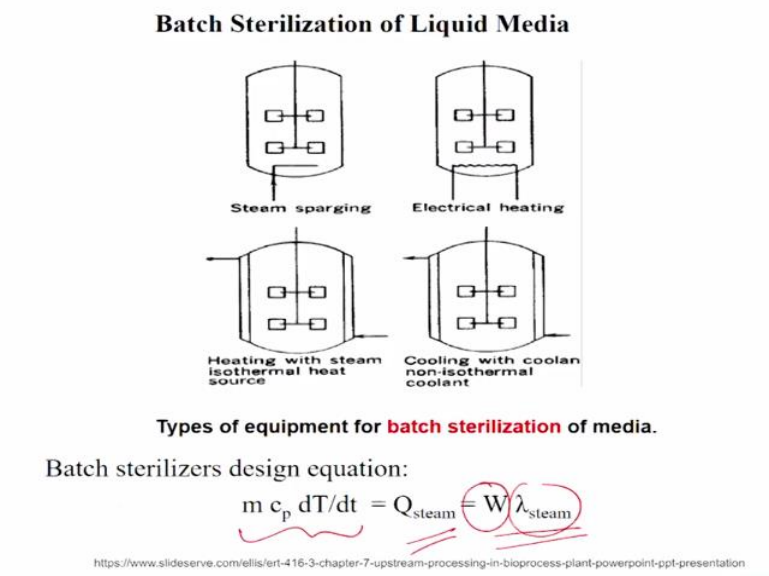

Now let us try to characterize the batch sterilization of the liquid medium. So, we know that there are different ways by which the media can be sterilized in batch processes. One can do direct steam sparging. There are electrical heaters which can be used or heating with steam through an isothermal heat source and then cooling with the coolant which is a non-isothermal coolant.

So, the design equation for the batch sterilizers because the rate at which the temperature of the medium would now change during the sterilization would depend on the let us assume that it is the steam sterilization process will depend upon the heat which is being released by the steam which can be given as W times lambda of steam. So, this is the latent heat and W is the weight of the steam or the flow rate of the steam.

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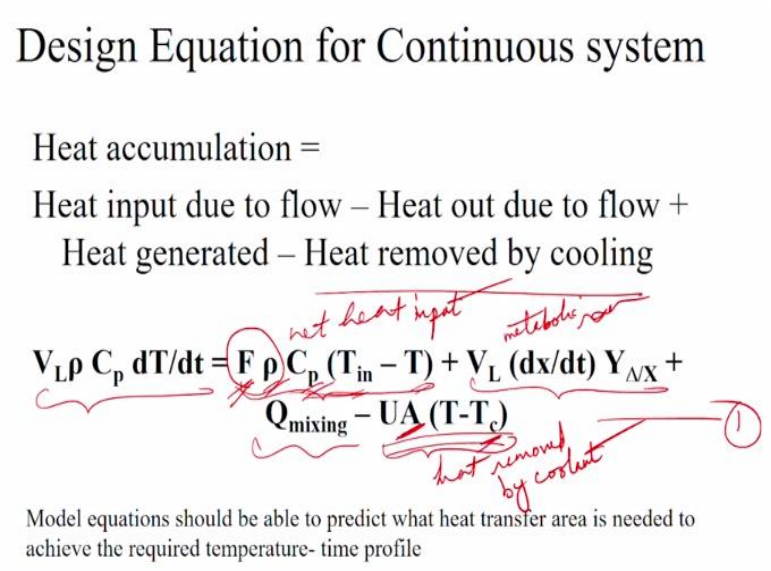

So, the design equation for a continuous system this will be heat accumulation which will be equal to the heat input due to the flow minus the heat out due to the flow plus if any heat is getting generated like in case of metabolic heat minus the heat removed by the cooling. So, this is an overall mass balance for the heat. So, the term on the LHS this defines the rate of heat accumulation.

The first term in the RHS this is nothing but the rate at which the heat is coming inside and the rate at which the heat is leaving where the incoming stream has the temperature T in and the outgoing stream let us assume has the temperature T. So, this is the net heat input. This is the heat generated due to metabolic reactions or cellular growth. Q mixing is also a part of heat generated and then heat removed due to coolant is being governed by the term given here the last term.

So, this is heat removed by the coolant. Then F was your volumetric flow rate of the continuous medium, rho is the density of the medium, C p is your specific heat capacity. So, F into rho is your mass flow rate of the heat multiplied by C p times delta T will give you the rate at which the heat is being input the net. Now this equation given here can finally be used to predict the heat transfer area is required to achieve the required temperature profile of the fermentation medium given the coolant temperature.