Process design Decisions and Project Economics
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Module - 7
Cost Diagrams and Quick Screening of Process Alternatives
Lecture - 34
Assessment of process Alternatives with Cost Allocation Diagram (Case Study of Hydrodealkylation Process)

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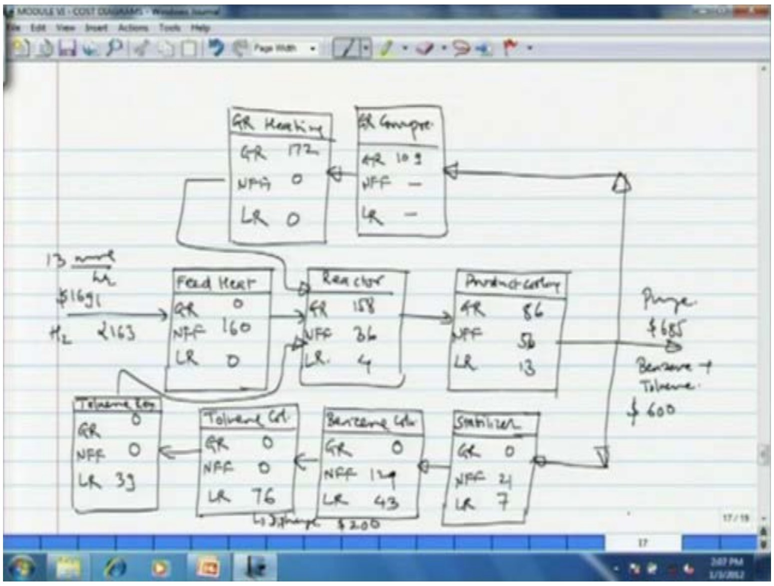

Welcome, in the previous lecture we saw as how we can convert a complicated cost diagram of an HAD process, which is heat integrated into two simple structures; first is the lump cost diagram that what we saw in the previous lecture, and then the cost allocation diagram, that you see on the screen at the moment. What we did is that, we identified the cost components, the operations that are cost intensive like for example, reaction, product cooling, feed heating, recycle heating and then separation of the reproducts and gas recycle, and compression and heating. And then we converted the process flow sheet into first a lump cost diagram, in which we had several operations listed. And thereafter we allocated the total cost for each operation to the three streams that are involved in it.

We identified three streams or what we can call as cost elements, that is the net fresh feed, toluene plus hydrogen and with impurity of methane then the gas recycle stream and the liquid recycle stream. And then we allocated the total cost of each of operation that we identified to the three streams, and then what we developed was a cost allocation diagram. Now, this cost allocation diagram can help us screen certain process alternatives, that it will help us in finding the economic incentive involved in each of the process alternative. Now, what are these process alternatives, let us first list these process alternatives, the design decisions, that we need to make at various levels.

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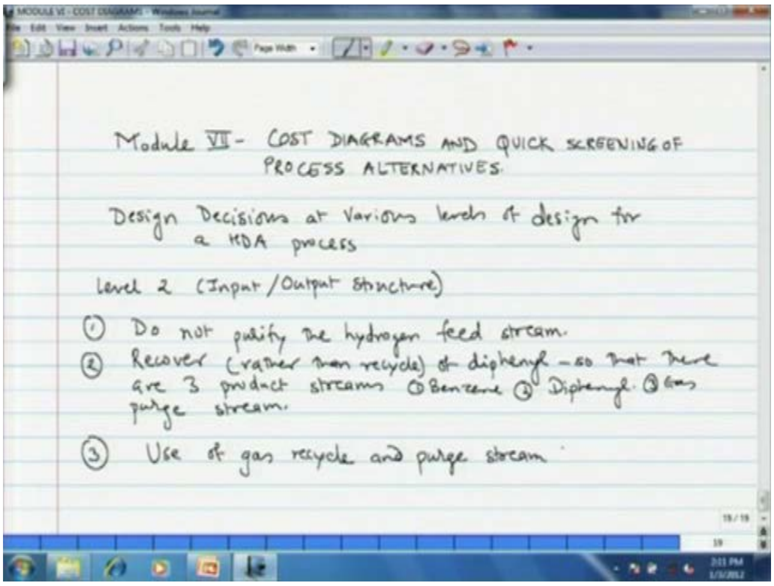

Module VI - COST DIAGRAMS AND QUICK SCREENING OF PROCESS ALTERNATIVES.

Design Decisions at Various levels of design for a HDA process

Level 2 (Input / Output Structure)

① Do not purify the hydrogen feed stream.

② Recover (rather than recycle) of diphenyl – so that there are 3 product streams ① Benzene ② Diphenyl ③ Gas purge stream.

③ Use of gas recycle and purge stream

Design decisions at various levels of design for a HDA, hydrodealkylation process now, I will not repeat the chemistry of hydrodealkylation, we have seen it several times before. Now, level 2, first we have to decide, the first level is whether to go for a batch or continuous operation and we have already decided to for a continuous process. So then the level 2 is the input output structure of flow sheet here, we have several alternatives, first is, do not purify the hydrogen stream the feed stream of hydrogen, which contains methane as an impurity.

Then second, recover rather than recycle of the diphenyl, diphenyl is a reversible side product so that, there are three product streams. First benzene, the main product then second diphenyl, the side product and third is the gas purge stream and the third decision was, whether to use a gas recycle and purge stream. We saw that, gas recycle and purge stream is essential in case, impurities are or byproducts are generated in the process.

If these are continuously recycled then they build up in the process and finally, they over take the process, The concentration of these byproduct or inerts need to be kept below a certain limit and therefore, we have to purge, throw off certain streams, which will reduce the concentration of those byproducts or the inerts. So, at level 2, input output structure of the flow sheet, we have three decisions to make.

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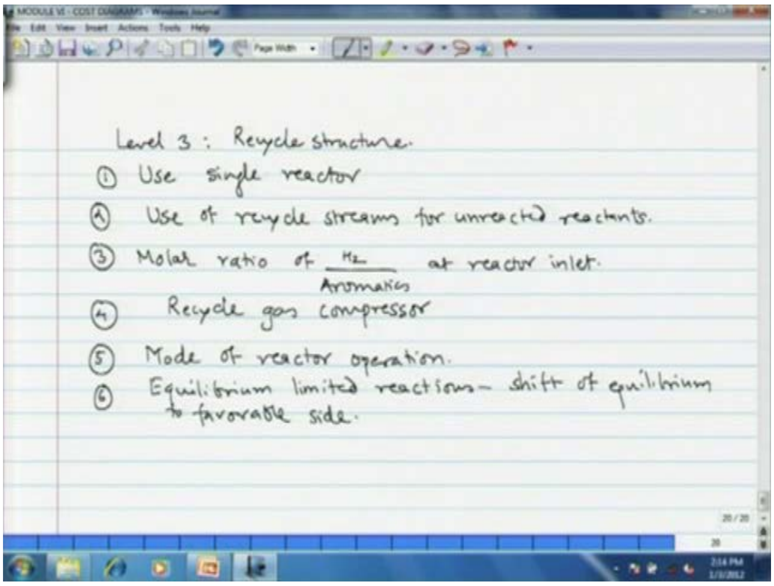

Level 3 : Recycle structure.

① Use single reactor

② Use of recycle streams for unreacted reactants.

③ Molar ratio of $\frac{H_2}{\text{Aromatics}}$ at reactor inlet.

④ Recycle gas compressor

⑤ Mode of reactor operation.

⑥ Equilibrium limited reactions – shift of equilibrium to favorable side.

Then, the next level, level 3 the recycle structure of flow sheet here, we have several decisions, how many reactors now, we have a single process, a vapor face process. Therefore, we have to use a single reactor, that point we note, use single reactor, the reaction is non-catalytic. Then second, use of recycle streams for unreacted reactants, the liquid reactant toluene and the gas reactant hydrogen then the next is molar ratio of hydrogen to aromatics at the reactor inlet.

Now, I already told you the role of excess hydrogen that is fed to the process, the primary objective of excess hydrogen is to force the reaction of toluene, the limiting reactant to completion. However, it has several other roles to play like hydrogen prevents coking, it burns of the coke deposited on the reactor wall then it can also act as a heat diluent in the system so as to, control the reactor temperature. So, the molar ratio of H 2 to aromatics at the rector inlet is a decision to make.

Then, fourth decision, the recycle gas compressor then fifth decision, the mode of reactor operation, whether to go for adiabatic or isothermal. Then finally, the equilibrium constraints, if any product is revisable then how we can minimize the production of that particular byproduct by shifting the equilibrium to the favorable side, shift of equilibrium to favorable side.

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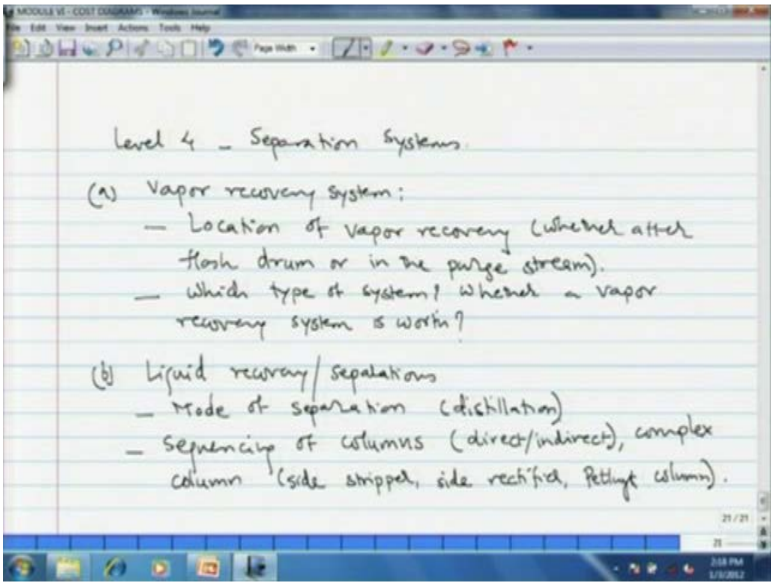

Level 4 – Separation Systems

(a) Vapor recovery system:
- Location of vapor recovery (whether after flash drum or in the purge stream).
- Which type of system? Whether a vapor recovery system is worth?

(b) Liquid recovery / separations
- Mode of separation (distillation)
- Sequencing of columns (direct/indirect), complex column (side stripper, side rectifier, Petlyuk column).

Then, level 4 that is, the separation structure of the flow sheet, we divide this level 4 into two parts, first a that is, vapor recovery system. Now, whether to, where to put the vapor recovery system, location of vapor recovery system, whether after the flash drum or in the purge stream. Then second decision associated with vapor recovery system is, which type of system to use, whether to go for absorption, adsorption, membrane separation.

And second is, whether a vapor recovery system is worth, that is also a question to be answered, we have to do an economic analysis to see the benefits and also the operating cost of the vapor recovery system. So, that is as regards the vapor recovery system now, next is part b, the liquid separation system or liquid recovery on separation. We have three liquid components benzene, toluene and diphenyl, now there are several options for separation of these components.

But, the most favorable operation in terms of cost, in terms of expertise, in terms of the knowhow, that is available is distillation. So, first decision that we make, is the mode of separation and here, we list distillation as our first choice. Then the sequencing of columns is another decision to make, whether to go for a direct system or indirect sequence, whether to go for complex columns such as side stream stripper, side stream rectifier or petlust column so on and so forth. Then, the question about the light ends, the light ends means essentially the smaller hydrocarbons like methane, ethane, ethylene, propylene, propane, butane, butylene, 1 2 butadiene, 1 3 butadiene so on and so forth.

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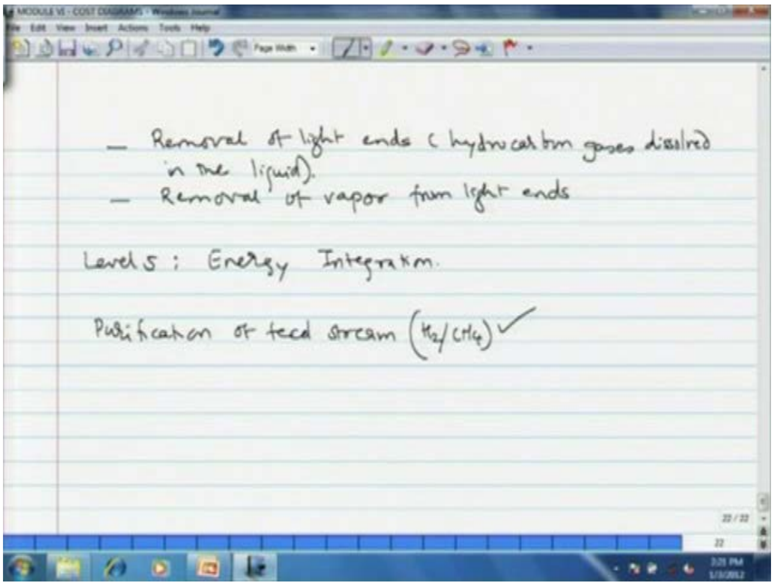

- Removal of light ends (hydrocarbon gases dissolved in the liquid).
- Removal of vapor from light ends

Level 5 : Energy Integration.

Purification of feed stream (H_2/CH_4) ✓

So, these light ends are to be removed through a stabilizer column, light ends is essentially the gas that is dissolved in the liquid, hydro carbon gases and then removal of vapor from light ends. Llight ends will always contain some vapor of benzene and toluene so removal of this particular vapor is essential, before you decide the fate of light ends usually, the light ends are used as fuel for captive consumption.

And then finally, comes the level 5 decision, that is the energy integration now here, we have several options available, we have already seen one option, in the tutorial we will see another option, that is available for energy integration. Now, we can proceed through this list of decision one by one and try to evaluate this net savings, that are associated with changing of any of the decision.

Use of cost diagram, is to identify the largest cost and then identify the decision having greatest impact on this cost. Now, for the HDA process, the largest cost item is the use of excess raw material and decision of altering this cost is made at level 2 that is, input output structure of the flow sheet. The next important cost are associated with gas recycle stream, which corresponds to level 3 decision.

So, let us see now, how we can evaluate certain process alternatives, let us see the first process alternative that is the, purification of feed stream, feed stream of hydrogen with impurity of methane. Now, is it worth to going for this, at the very first inspection we can find that, it is not worth doing so. Why, because methane is also generated as a byproduct in the process, when the toluene gets converted to benzene it gives out 1 mole of methane.

So, methane is already generated into the process so if there is any methane in the feed stream, it can be removed simultaneously with the reaction generated methane. So, as far as the purification of feed stream is concerned, we can find just by inspection that, it is not worth doing so because methane is also present as the reaction product in the process.

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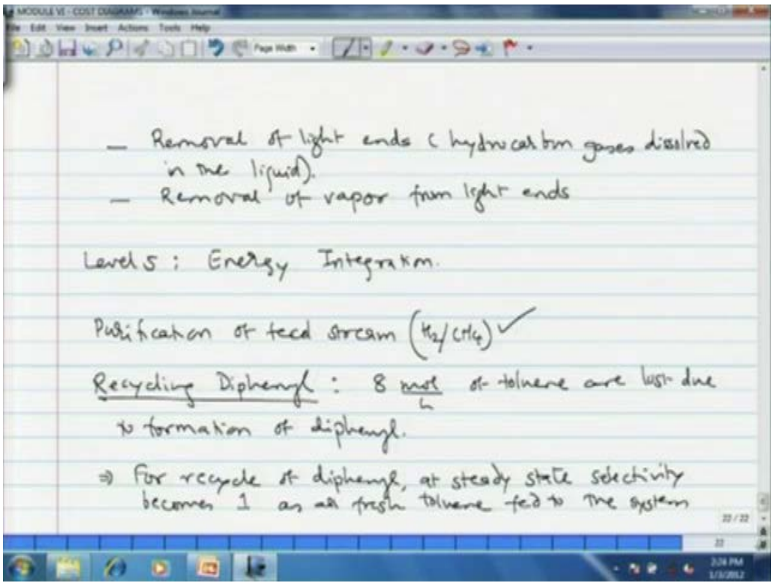

- Removal of light ends (hydrocarbon gases dissolved in the liquid).
- Removal of vapor from light ends

Level 5 : Energy Integration.

Purification of feed stream (H_2/CH_4) ✓

<u>Recycling Diphenyl</u> : 8 $\frac{mol}{h}$ of toluene are lost due to formation of diphenyl.

⇒ For recycle of diphenyl, at steady state selectivity becomes 1 as all fresh toluene fed to the system

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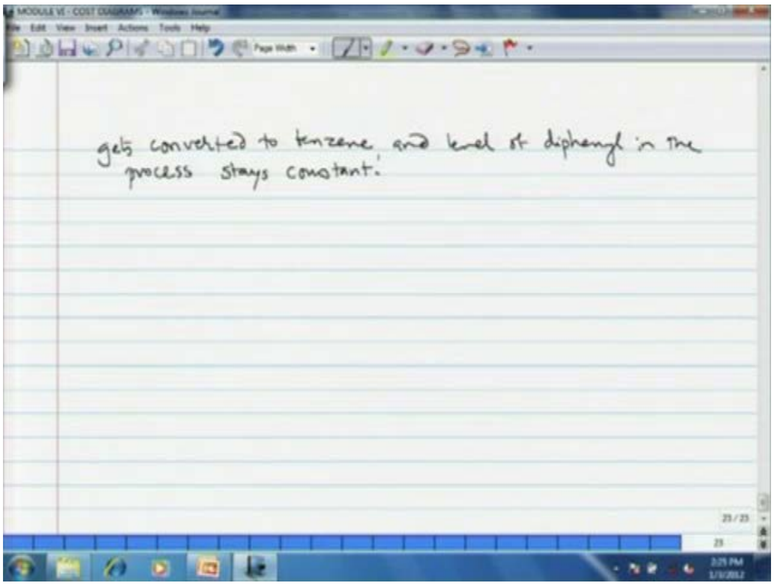
gets converted to benzene and level of diphenyl in the process stays constant.

Now, the next decision would be that of recycling of diphenyl now, this decision is likely to have high impact, because it will reduce the quantity of toluene that is lost in the form of diphenyl, recycling of diphenyl. From our calculations that we saw in module 2, flow sheet synthesis, for a production rate of benzene 265 moles per hour, selectivity of 0.99 or 0.98, we get typically 4 moles of diphenyl per mole of benzene.

So, from stoichiometry, 1 mole of toluene gives 1 mole of benzene and 2 moles of benzene combine reversibly to give 1 mole of diphenyl so per mole of diphenyl, that is formed the total toluene loss is of 2 moles. So, for 4 moles of diphenyl that are formed, for 265 moles per hour production rate of benzene, we get 8 moles of toluene has lost so that point we note, 8 mole per hour of toluene are lost due to formation of diphenyl.

Now, when we recover diphenyl and recycle, it builds up into the process but since it is a reversible byproduct, it will build to a certain level and then will remain constant. At that time, all of the fresh toluene that is fed to the process, will get converted only to benzene. Now, remember this point very, very clearly, when you recover diphenyl and recycle to extinction that means, it will build up into the process and will remain at steady at equilibrium level at that time, all of the fresh toluene that is fed to the system will get converted to benzene.

That means, at that time, at the steady state, the selectivity will be 1 so that point we note here, for recycle of diphenyl at steady state, selectively becomes 1, as all fresh toluene fed to the system gets converted to benzene and level of diphenyl in the process stays constant. Now, in the cost allocation diagram, we had noted that, the total loss of toluene in the form of diphenyl and also the vapor in the purge stream was 13 mole per hour, costing 1691000 dollars annually, now out of these 13 moles, we are going to recover 8 moles.

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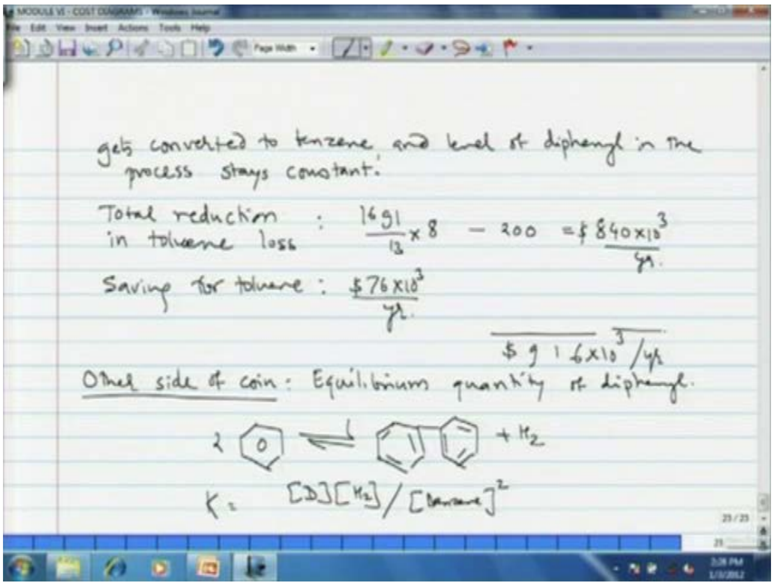

gets converted to benzene and level of diphenyl in the process stays constant.

Total reduction in toluene loss : $\frac{1691}{13} \times 8 - 200 = \$ \frac{840 \times 10^3}{yr.}$

Saving for toluene : $\frac{\$ 76 \times 10^3}{yr.}$

$\overline{\$ 916 \times 10^3 / yr}$

Other side of coin: Equilibrium quantity of diphenyl.

$2 \text{ benzene} \rightleftharpoons \text{diphenyl} + H_2$

$K = [D][H_2] / [Benzene]^2$

That means, the total loss will be reduced by the following quantity 1691000 dollars for 13 moles out of which, 8 moles going to recover so this much is the reduction. However, the diphenyl was also used as the fuel in the process now, when we are recycling diphenyl, that particular option is not available so we will have to buy the fuel, worth that much quantity.

So, 200000 dollars, which was the annual fuel cost of the diphenyl is now subtracted from the savings because we have to buy fuel worth that much quantity so the total saving per year due to recycling of diphenyl is 840000 dollars. Now, when we decide to recycle diphenyl, we do not need a toluene column, one column is enough to take of benzene and then the bottoms of that particular column, which contains toluene plus diphenyl can be recycled.

So, the saving for toluene column is also a benefit and the cost of toluene column, as we found was 76000 dollars, the annualized capital cost, so that is saved, together this turns out to be close to a million dollars saving. Now, what is the penalty or the other side of the coin, that diphenyl will now get built up into the process and we will stay steady, at the equilibrium level.

So, first of all we have to find out, what is the equilibrium quantity of diphenyl that is formed and we have to oversize all over equipment to accommodate that much of diphenyl, equilibrium quantity of diphenyl. Now, a diphenyl is formed through this reversible reaction and therefore, the equilibrium constant is quantity of diphenyl or concentration of diphenyl divided by concentration of hydrogen, divided by concentration of benzene squared.

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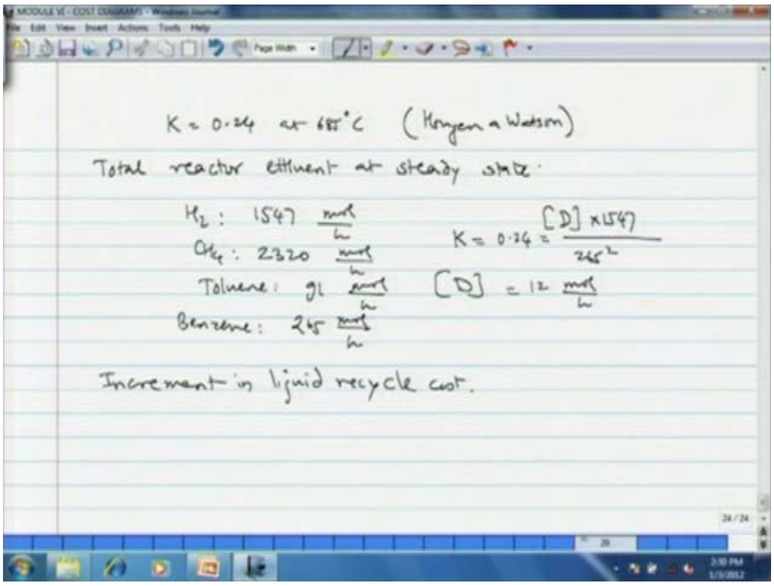

$K = 0.24$ at 685°C (Hougen & Watson)

Total reactor effluent at steady state:

H_2 : 1547 $\frac{mol}{h}$

CH_4 : 2320 $\frac{mol}{h}$

Toluene : 91 $\frac{mol}{h}$

Benzene : 265 $\frac{mol}{h}$

$$K = 0.24 = \frac{[D] \times 1547}{265^2}$$

$$[D] = 12 \frac{mol}{h}$$

Increment in liquid recycle cost.

Now, the value of k is 0.24 at 685 degree centigrade, this particular value has been taken from the book Hogan and Watson, the book of Hogan and Watson chemical process calculations. And then we have to calculate the material balance, the material balance I am going to give you directly, you can do it yourself, look into the homework of module 2 where, we have already done these types of calculations.

The total reactor effluent at steady state will comprise of hydrogen 1547 moles per hour, methane 2320 moles per hour, toluene 91 mole per hour, benzene 265 mole per hour. And now, we substitute these values in the equilibrium constant relation k, is equal to 0.24 is equal to diphenyl quantity into 1547 divided by 265 square. So, the equilibrium quantity of diphenyl at steady state comes out to be 12 mole per hour, we will have to oversize all our equipment to accommodate this much of diphenyl.

As we have seen in the cost correlation exercise, the cost does not carry linearly, the cost typically varies to the exponent of 0.6, but what we will do now is that, we will assume a linear variation of the cost, operating cost. Let us say, we have to oversize reactor to accommodate these 12 moles per hour, so we assume that the reactor cost goes up by that much quantity and then same the liquid recycle cost, etcetera.

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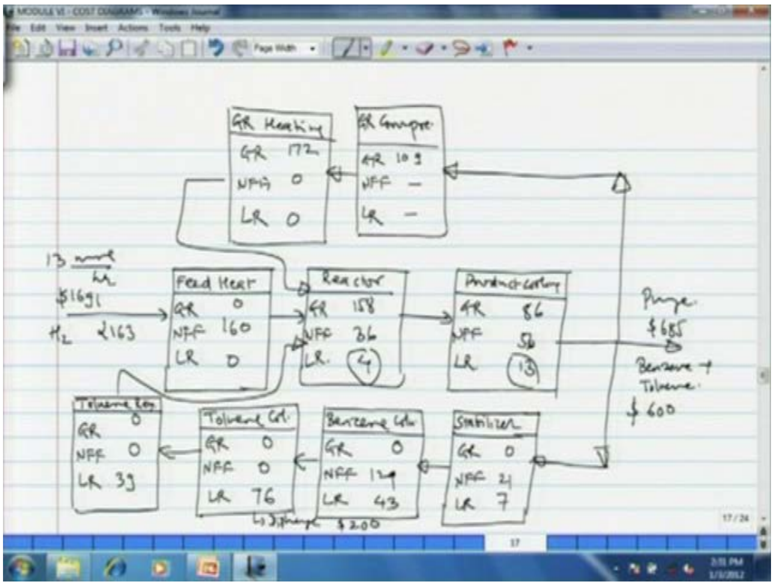

Let us find out, what is the increment in the cost of liquid recycle now, if you go to the cost allocation diagram and identify all of the quantities that are associated with liquid recycle. For example, reactor total cost was 198000 dollar annual capital cost and 4000 dollars were allocated to the liquid recycle, similarly for product cooling 13000 dollars were allocated to the liquid recycle. So similarly, in the cost allocation diagram, you pick up those cost that are associated with liquid recycle stream and then add them up.

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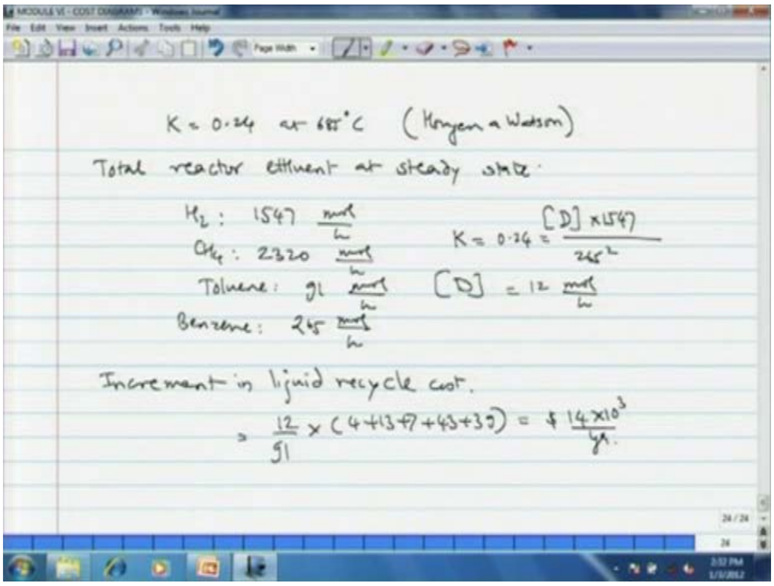

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$[D] = 12 \frac{mol}{h}$

Increment in liquid recycle cost.

$= \frac{12}{91} \times (4 + 13 + 7 + 43 + 39) = \$ \frac{14 \times 10^3}{yr.}$

We will find that, the liquid recycle cost will go up by quantity 12 by 91 why, because when diphenyl was recovered as the side product, 91 moles of toluene were recycled. So, whatever cost, that are given for the liquid recycle or for the 91 moles now, the liquid recycle will be 91 plus 12. So obviously, all of the cost will go up by ratio 12 by 91 so 12 by 91 into 4 plus 13 plus 7 plus 43 plus 39, look the cost allocation diagram to pickup these quantities and then all of these will add up to 14000 dollars per year.

Now, if you compare this incremental liquid recycle cost to almost 1 million dollars of saving, you can see that the increment is negligible so it is worth going for the recycling of diphenyl.

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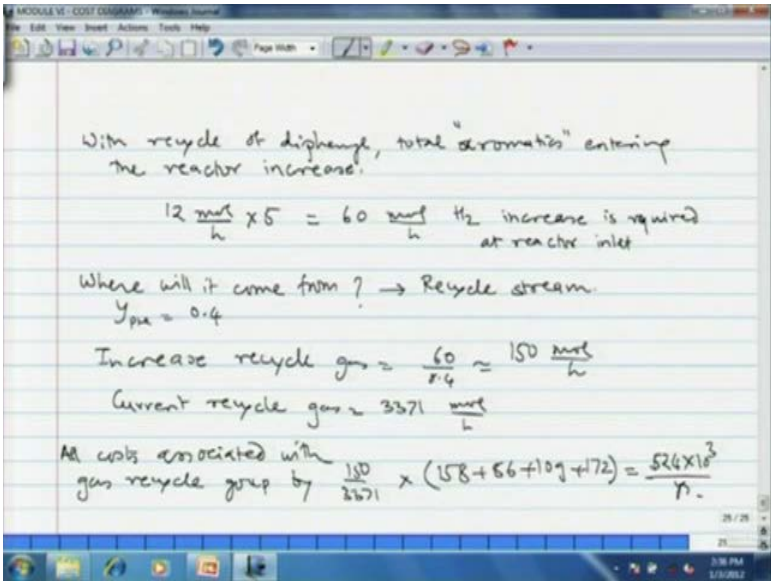

With recycle of diphenyl, total "aromatics" entering the reactor increase.

$12 \frac{mol}{h} \times 5 = 60 \frac{mol}{h}$ H_2 increase is required at reactor inlet

Where will it come from ? → Recycle stream

$y_{PH} = 0.4$

Increase recycle gas $= \frac{60}{0.4} \simeq 150 \frac{mol}{h}$

Current recycle gas $= 3371 \frac{mol}{h}$

All costs associated with gas recycle go up by $\frac{150}{3371} \times (158+56+109+172) = \frac{524\times10^3}{yr.}$

Now, with the recycle of diphenyl, the total aromatics that enter the reactor increases now, I am using word aromatics, I am not using word diphenyl or toluene or benzene, I put them, all of them in the same bracket as aromatics, total aromatics entering the reactor increases. Now, if I have to maintain the molar ratio to be 5 as to 1, I have to increase the quantity of hydrogen; that is entering into the process.

That means, additional 12 mole per hour of aromatic entering, I have to admit into the reactor, 5 moles for that particular 12 moles so total 60 moles per hour of hydrogen increase is required at the reactor inlet. Now, where will this hydrogen come from, should I add more of fresh gas only to be purged, that is not a good idea so what I will go for is, to increase the recycle of the gas. This I will try to get that much of hydrogen, extra hydrogen through the recycle stream however, the recycle stream composition of hydrogen is only 40 percent, Y ph was 0.4, if you remember.

I have noted this values at the beginning of this module therefore, I have to increase the recycle gas by quantity 60 by 0.4 that is, something like 150 moles per hour. The current recycle gas with recovery of diphenyl was 3371 moles per hour, now that recycle gas will go up by 150 mole. So obviously, all cost, that are associated with gas recycle will also go up by ratio 150 by 3371.

So, from the cost allocation diagram, we pickup these values gas recycle, gas recycle compression, heating reactor so on and so forth, product cooling, all the cost that are associated with gas recycle, sum them up and multiply them by 150 by 3371, that is the additional cost, that you are going to incur. So, 150 divided by 3371 into 158 plus 86 plus 109 plus 172, so that is together 24000 dollars per year and then the net saving.

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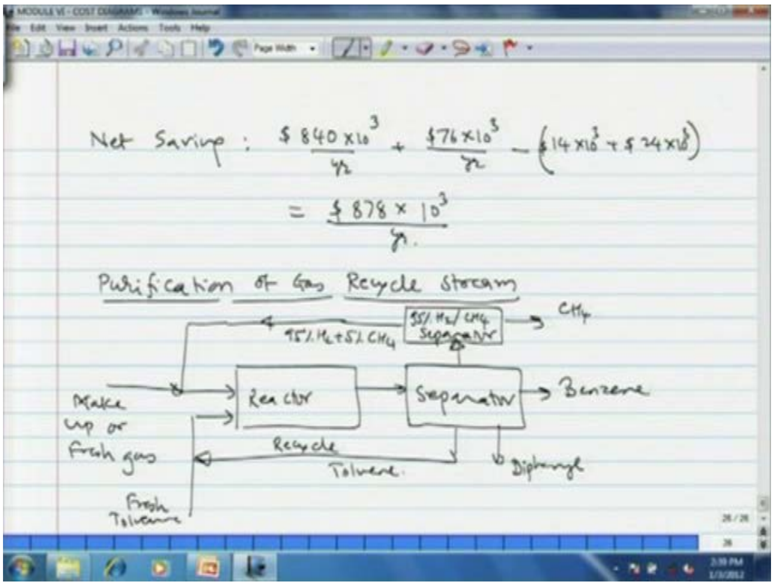

Net Saving : $\frac{\$\,840 \times 10^3}{yr} + \frac{\$\,76 \times 10^3}{yr} - \left(\$\,14 \times 10^3 + \$\,24 \times 10^3\right)$

$= \frac{\$\,878 \times 10^3}{yr.}$

Purification of Gas Recycle Stream

Net saving is the cost of toluene that is saved, that we estimated at 840000 dollars per year plus the cost of toluene column, that we eliminated minus the cost of the liquid recycle stream, 14000 dollars and the cost of gas recycle stream, 24000 dollars. So, the net saving is 878000 dollars annually, which is significantly large quantity so as to consider this alternative, and go for more detailed calculations.

Obviously, here, we have made an assumption, that all cost rise linearly but remember, we are at the very basic level of the design, we are working only with parent paper. And therefore, we can make these kind of approximation so as to, gain an insight into the relative impact of each of the process alternative. If it is attractive as in the present case, we can go now for further more detailed calculations so that effort is justified.

Now, we can similarly evaluate another alternative of purification of the gas recycle stream now, what we do is that, we change our flow sheet side slightly. Now, what I am going to draw is the recycle structure of the flow sheet, I have the reactor followed by separator and from separator, the gas that emerges is filtered through a membrane module, which recovers entire hydrogen and 5 percent methane.

And it generates a stream, that contains 95 percent of hydrogen and 5 percent methane, which is very much similar to the feed gas composition and then it is recycled. But remember, the recycled gas contains entire unreacted hydrogen, that point remember very thoroughly. Then we have the makeup of fresh gas then the toluene, fresh toluene plus the recycle toluene and then we have the product of diphenyl benzene and then a purge stream, which contains only methane because all of the hydrogen is recovered with some quantity of methane.

So, this is the new recycle structure of the flow sheet, after we separate or purify the gas recycle stream. Now, you have to do a simple material balance, that I am leaving as an exercise for you, you can very easily do it. Taking the previous example as a base case where, we had 265 moles per hour of benzene production, same selectivity, same per pass conversion, etcetera. Taking same values, you can very easily do this material balance, which I am going to give now, exact calculation I leave to you because those are pretty easy.

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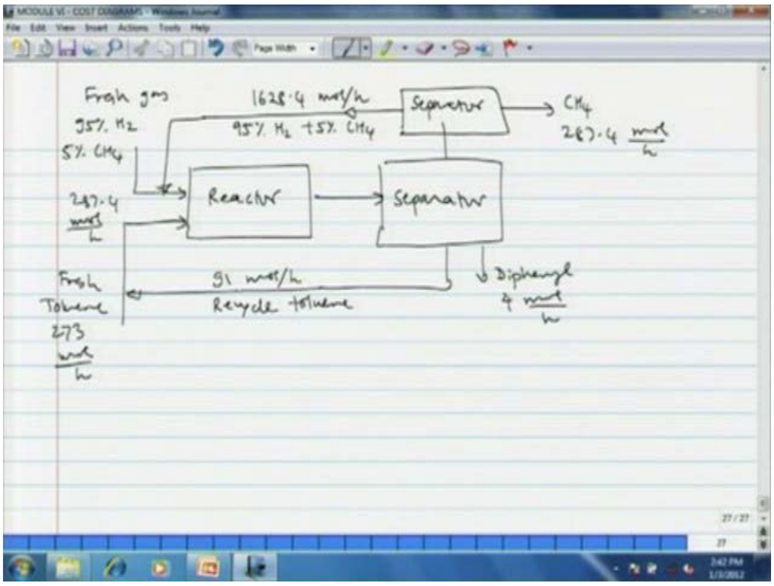

I am again going to draw the same flow sheet, but now I am going to put the molar flow rates, the fresh gas that contains 95 percent hydrogen, 5 percent methane is 287.4 mole per hour. Then fresh toluene will be same as before 273 moles per hour then recycle toluene will also be same as 91 moles per hour, diphenyl that will come out will be 4 mole per hour. So, you can see that, gas purification is not going to affect the liquid phase mass balance significantly however, what we will change, is the gas recycle balance.

Now, separator is going to generate a stream that contains 95 percent hydrogen but recovers entire hydrogen and then this stream will be 1628.4 mole per hour. Composition 95 percent hydrogen plus 5 percent methane and the purge gas will contain only methane, that will be 287.4 mole per hour, so this is the new material balance. Now, we have to evaluate the economic saving and additional expenditures, what we will save in this case. Like in the previous case, we saved the cost of toluene that was lost, as diphenyl now here, we will recover the cost of excess hydrogen fed to the system.

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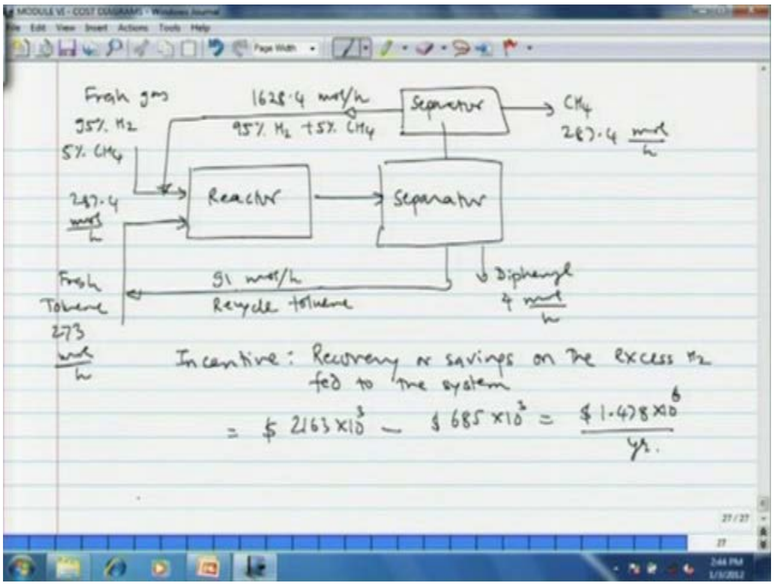

Incentive: Recovery or savings on the excess H_2 fed to the system

$$= \$\, 2163 \times 10^3 - \$\, 685 \times 10^3 = \frac{\$\, 1.478 \times 10^6}{yr.}$$

I will write here, incentive, incentive is the recovery or savings on the excess hydrogen fed to the system, which was lost in the purge stream. Now, if you remember, we had listed that quantity also in the cost allocation diagram, the cost of excess hydrogen that was lost annual cost was 2163000 dollars, so more than 2 million dollars so it is the significant cost, that is lost.

So then net saving is 2163000 dollars; however, the purge stream that was used, the purge stream that was generated from the process was also used as a fuel and that fuel was worth 685000 dollars a year. Now, when we are not going to have hydrogen in the purge, this 685000 dollars worth of fuel, we have to buy extra so that is an additional expenditure.

So, the net saving in the present case is 2163000 dollars minus this 685000 dollars so that is total 1.478 million dollars, which is quite a large amount plus 21.5 million dollars.

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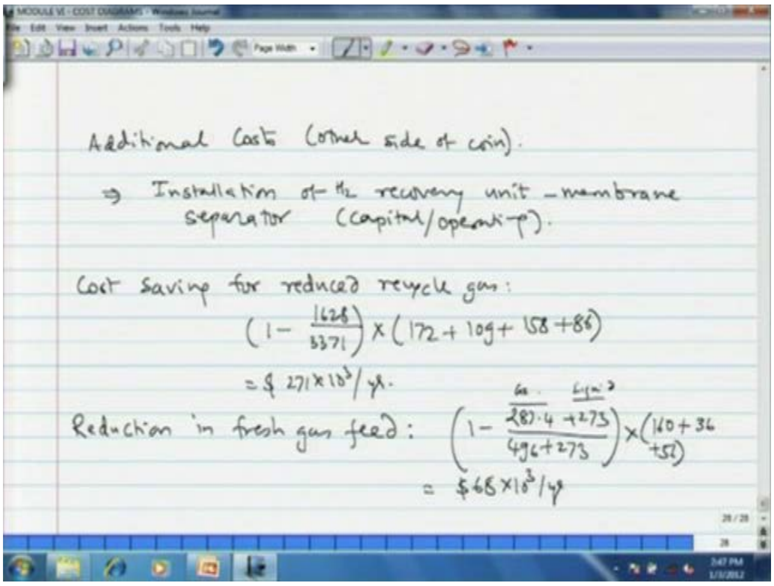

Additional Costs (other side of coin).

⇒ Installation of H_2 recovery unit – membrane separator (capital/operating).

Cost saving for reduced recycle gas:

$$\left(1-\frac{1628}{3371}\right)\times(172+109+158+86)$$

$$= \$\,271\times10^3/\text{yr}.$$

Reduction in fresh gas feed:

$$\left(1-\frac{287.4+273}{496+273}\right)\times(160+36+52)$$

$$= \$\,68\times10^3/\text{yr}$$

Now, what are the additional cost, that we are going to incur or the other side of the coin now first of all, the installation and operation of the hydrogen recovery unit itself is a major cost so that point we note. But, at the moment, we do not have any cost information on it, we do not have any cost correlation for such membrane module. So, we are unable to quantify but we list that particular cost qualitatively, installation of hydrogen recovery unit, membrane separator, capital cost as well as operating cost.

Now, we are going to reduce the gas recycle stream, so all the cost, that are associated with gas recycle will also go down, that point we did not mention in the previous thing but now, we do it. So, it is not an additional cost but cost saving for a reduced recycle gas is 1 minus 1628 divided by 3371, now the previous recycle gas flow was 3371 moles per hour, the new one is 628, so 1 minus this particular quantity is the saving.

And then you pickup all the cost that are associated with gas recycle in the cost allocation diagram, that I am writing now directly, you can refer to the previous lecture. These are 271000 dollars annually and then we also get a reduction in fresh gas feed now, the previous fresh gas was 496 moles, which is now 287.4 moles however, the toluene remains the same.

So, that we add to numerator and denominator and then all the cost that are associated with fresh feed will go down by quantity 1 minus this particular ratio, 287.4 moles of gas and 273 moles of liquid, liquid remains the same, gas changes. And then all the cost that are associated with net fresh feed, we sum up like. For example, this 160 then 36 and 56, that point these cost we add, 160 plus 36 plus 56 and together this gives 68 dollars.

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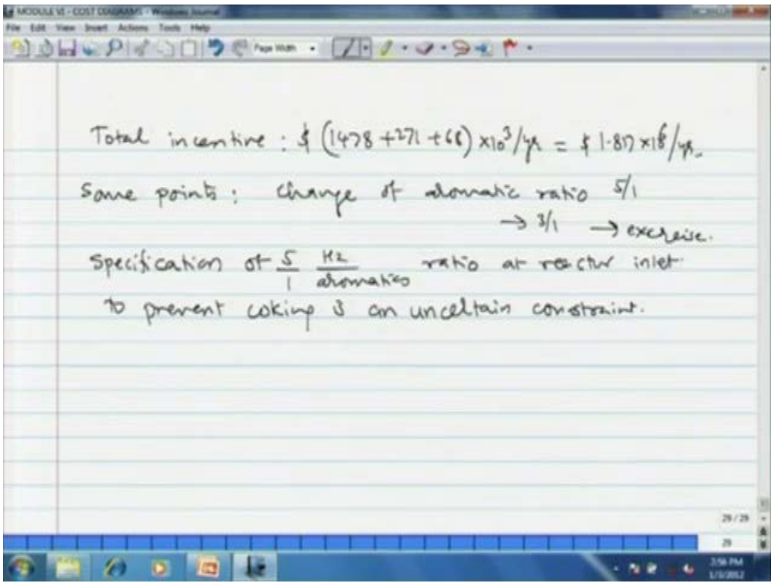

Total incentive : $\$ (1478 + 271 + 68) \times 10^3/\text{yr} = \$ 1.817 \times 10^6/\text{yr}.$

Some points : change of aromatic ratio 5/1 → 3/1 → exercise.

Specification of $\frac{5}{1}$ $\frac{H_2}{\text{aromatics}}$ ratio at reactor inlet to prevent coking is an uncertain constraint.

So, the total saving or total incentive for using a gas purification system is 1478 plus 271 plus 68000 dollars annually and that is, 1.8 million dollars per year. Now, there are some points, that are qualitative at this moment, that we would like to note now, if you are going to reduce the recycle gas, we have to identify, what are the additional roles that recycle gas played. Large recycle of methane, 60 percent methane was there in the recycle gas acted as a heat carrier or heat diluent for the system because of it is, high heat capacity.

Now, once we are reducing the quantity of methane in the recycle gas from 60 percent to only 5 percent, that flow will limit the exit temperature of the adiabatic reactor. If you remember in module 2, we had calculated the exit adiabatic temperature of the reactor and then it was below the limit of 1300 degrees Fahrenheit, which was the limit for the thermal cracking or coking of the reactor and therefore, we decided to operate the reactor adiabatically.

Now, when the quantity of recycle methane is going to go down, that particular advantage is no more available to us because 60 percent methane was able to control temperature, 5 percent methane will not be able to control temperature to that level. So, temperature surge will occur and therefore, we have to modify the reactor design so as to, have additional heat removal system into the reactor. Accommodate the additional heat removal system may be in the form of jacket, may be in the form of cooling coils so on and so forth.

But, somehow, we have to make arrangements for the removal of heat, that was otherwise carried out by methane so as to, control temperature. So, that cost will also add up, that cost we are unable to quantify at the moment but you can imagine that, it would be a significant cost. But now, 1.8 million dollars is itself is a significant number is significantly large number to go for additional calculations so what we have seen now is that, the cost diagrams gives us a very easy way of evaluating process alternatives, the relative economic impact of particular alternative.

Now, what are the other decisions, that we can make for example, change of process constraint, that change of aromatics ratio from 5 as to 1 suppose, we make as let us say, 3 as to 1. Then what will be the cost that is associated or what will the cost saving, that is associated with such a decision, we can find out from that particular cost allocation diagram.

Now, this I leave as an exercise for you but remember that each time there will be a other side of the coin, as we just saw for methane, that recycle methane was able to control temperature. Now, when you do not have recycle methane, temperature surge will occur and you have to take additional efforts for control temperature. So, that is for this particular lecture, in the next lecture we shall see an alternative energy integrated flow sheet for hydrodelakylation process and try to develop a cost allocation diagram for it.

What we saw was one alternative but there are many other alternatives, that could be possible, we shall take that particular alternative and we will take a case of recycle of diphenyl. That means, we already work at selectivity equal to 1 and then we shall see, as how we can develop a cost allocation diagram and then whether we can test any further process alternative.

Now, we shall see one more process alternative, which can be evaluated using the cost diagram that is, the change of hydrogen to aromatics ratio from 5 as to 1 to some lower value, that will help us reduce the cost of hydrogen. Now, why 5 as to 1, the specification of 5 as to 1 or H 2 to aromatics ratio at reactor inlet is an uncertain constraint. It appears, that the chemist has done numerous experiment and has by trial and error, has found out that at 5 as to 1, the coking is prevented. So, he has recommended the ratio 5 as to 1, but do we or is it a constraint on us to use it, we can alter it, we can reduce it so as to, reduce the cost.

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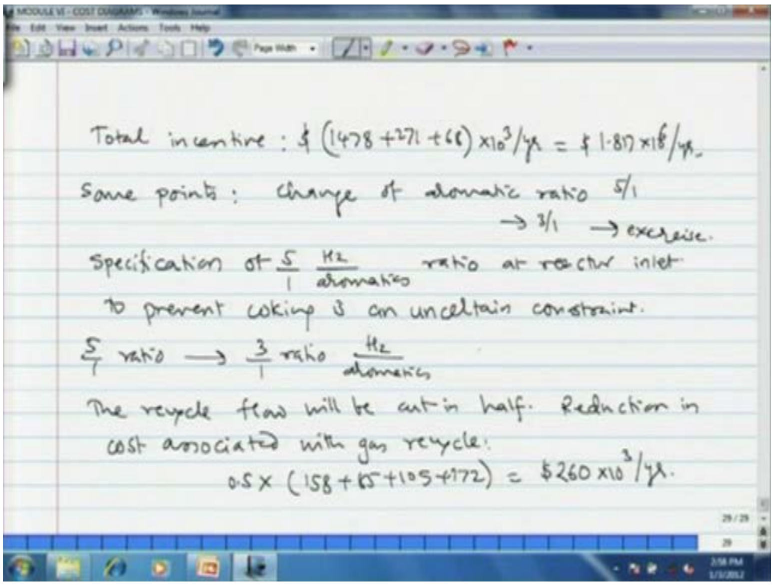

Total incentive : $ $(1478 + 271 + 68) \times 10^3/\text{yr} = \$ 1.817 \times 10^6/\text{yr}$.

Some points : change of aromatic ratio 5/1 → 3/1 → exercise.

Specification of $\frac{5}{1}$ $\frac{H_2}{\text{aromatics}}$ ratio at reactor inlet to prevent coking is an uncertain constraint.

$\frac{5}{1}$ ratio ⟶ $\frac{3}{1}$ ratio $\frac{H_2}{\text{aromatics}}$

The recycle flow will be cut in half. Reduction in cost associated with gas recycle:

$0.5 \times (158 + 65 + 105 + 172) = \$260 \times 10^3/\text{yr}$.

Now, let us say that, we reduce the 5 as to 1 ratio to something like 3 as to 1 ratio, H 2 to aromatics now obviously, this will give a lot of saving on hydrogen especially, the gas recycle flow is cut in half. Let us say, keeping the fresh feed constant, we are reducing the H 2 to aromatics ratio, net fresh gas is constant but H 2 to aromatics ratio is reduced so that means, essentially, we are reducing the gas recycle flow.

Now, if you reduce it from 5 as to 1 to 3 as to 1, the reduction is half and then the gas recycle flow will be cut in half. And therefore, the reduction in the cost associated with gas recycle flow will be the summation of all the cost, that are associated with gas recycle into 0.5. So, going back to the cost allocation diagram, we find the cost allocated with gas recycle, gas compression, heating, etcetera, and then we multiply that by half, 158 plus 85 plus 109 plus 172. So, together this gives a saving of 260000 dollars per year if we bring down the H 2 to aromatics ratio.

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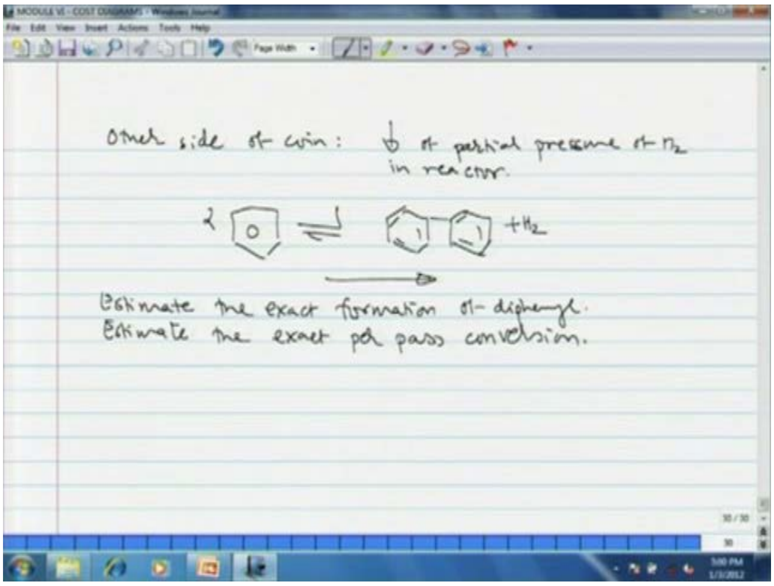

Other side of coin: ↓ of partial pressure of H_2 in reactor.

Estimate the exact formation of diphenyl.
Estimate the exact per pass conversion.

But, what is the other side of the coin, the major impact it will have is the decrease in the partial pressure of hydrogen in the reactor. Now, if this happens then the conversion of toluene will not be complete in the first place, that per pass conversion will decrease and secondly, hydrogen appears in the right hand side of the undesired reaction. Now, if hydrogen partial pressure is reduced, the equilibrium will shift towards this side, towards the diphenyl side so more of diphenyl will be formed so that is the other side of the coin.

Therefore, it is essential to verify experimentally, that operation with 3 as to 1 H 2 to aromatics ratio is possible, before a detailed design studies are undertaken. We have to estimate the exact formation of diphenyl and also the conversion, that will occur in case the hydrogen is reduced. So, this is how we have seen, as how cost diagrams are an effective means of summarizing cost information and how these can help us in quick screening of the process alternatives that is, for today’s lecture.

In the next lecture, we shall see a tutorial, in which we shall try to develop a similar cost allocation diagram for another energy integrated process alternative of the hydrodealkylation process. Now, in that process alternative, we shall already have diphenyl recycled into the process so that, the selectivity is 1. And then we shall, as how the different process alternative give an relative impact into the overall economics of the process.