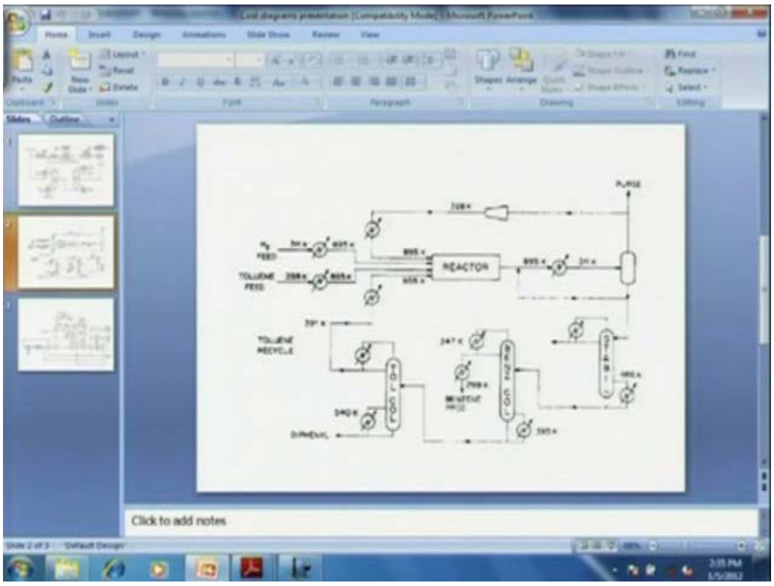
Process Design Decisions and Project Economics
Dr. V. S. Moholkar
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Module - 7
Cost Diagrams and Quick Screening of Process Alternatives
Lecture -35
Tutorial on Lumped Cost Diagram and Cost Allocation Diagram

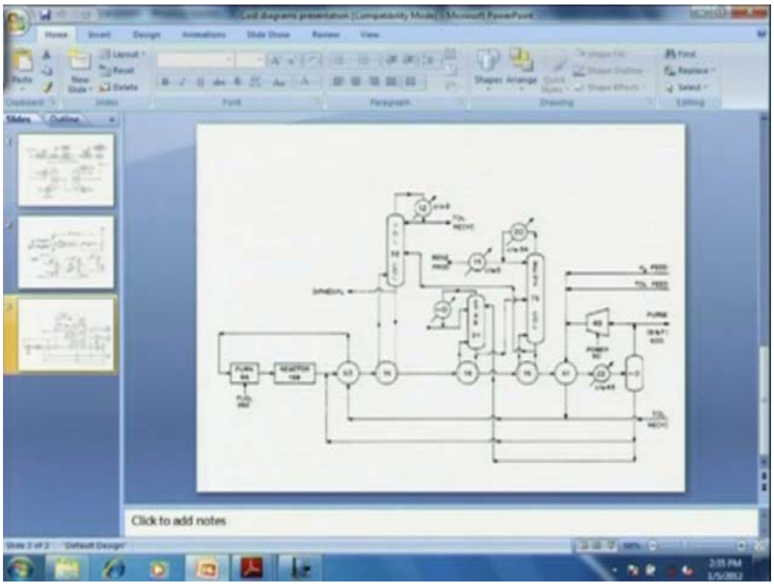
Welcome, we have started with the module on Cost Diagram and today we shall see a tutorial on it.

(Refer Slide Time: 00:37)



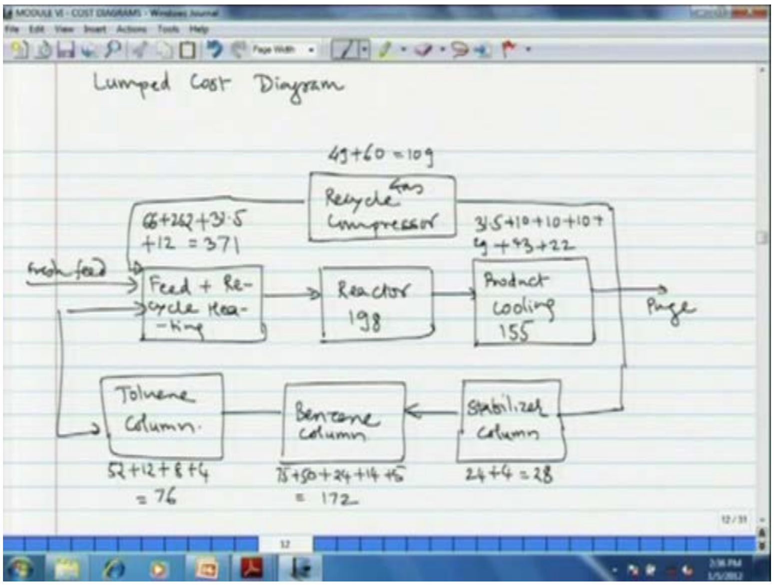
In the past 3 lecture we studied various aspects of the Cost Diagram, as how we can convert basic flow sheet into an energy integrated flow sheet.

(Refer Slide Time: 00:41)



To the cost diagrams we are prepared by putting the cost information right on to the flow sheet the annualized capital cost of the equipment was put inside the box that indicated the particular equipment and processing cost was allocated to a particular stream. A complicated cost diagram of an energy integrated hydro de alkalization process of toluene, was converted into a relatively simple diagram what we call lumped cost diagram.

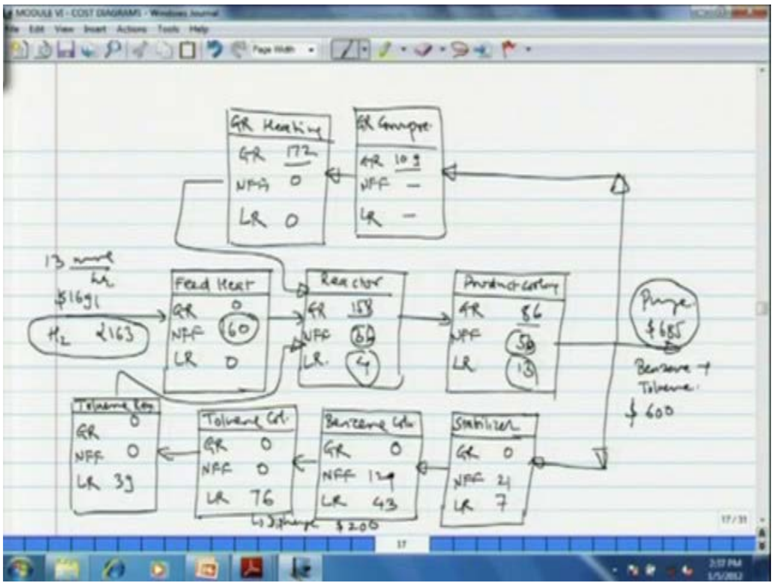
(Refer Slide Time: 01:14)



The lumped cost diagram was prepared by identifying the cost intensive operation in the flow sheet, and then summing up cost of the equipment that is involved in each of the operations. So, these operations were the feed and recycle heating, reactor, product cooling then gas recycle compressor and separation of the 3 liquid streams, benzene, toluene and xylene through 3 columns stabilizer columns, benzene columns, toluene columns.

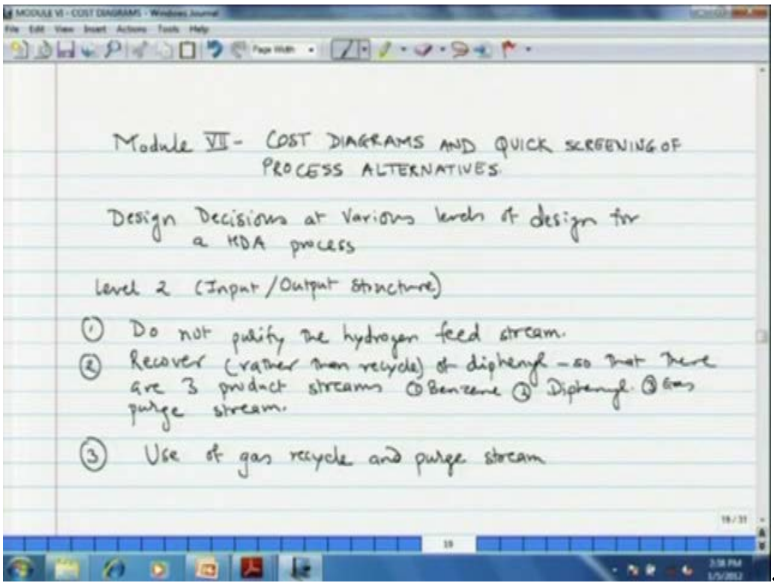
Then we distributed the cost of the common equipment to the 2 processes depending on the contribution of that particular process like for example, the major distribution was of the cost distribution of heat exchangers. And then the cost of heat exchanger was distributed in the inverse proportion of the film coefficient of the 2 streams that were involved in that particular exchanger, because the cost of heat exchanger is proportional or varies with the area of the heat exchanger. There after we converted this lumped cost diagram into cost allocation diagram.

(Refer Slide Time: 02:22)



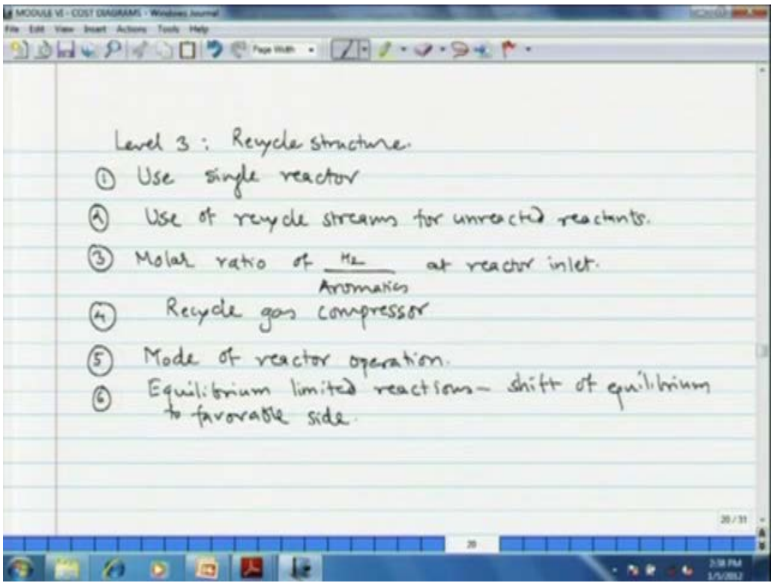
In which we distributed the particular cost for each operation to the 3 streams that were involved in the operation, these were called as the cost elements. Now, cost elements were 3 first the net fresh feed which is the sum of the gaseous feed that is hydrogen plus impurity of methane and also the toluene liquid feed then the, gas recycle stream which contain 40 percent hydrogen and 60 percent methane typically, and then the liquid recycle stream. And then we arrived at the cost allocation diagram that we see on the screen now, and there after we evaluated using this cost diagram, cost allocation diagram various process alternatives.

(Refer Slide Time: 03:12)



What were the process alternatives that we had at level 2 input output structure of the flow sheet we had the alternative of purifying the hydrogen feed stream then we had the alternative of recovery rather than recycle of the biphenyl then the use of the gas recycle in the purge stream.

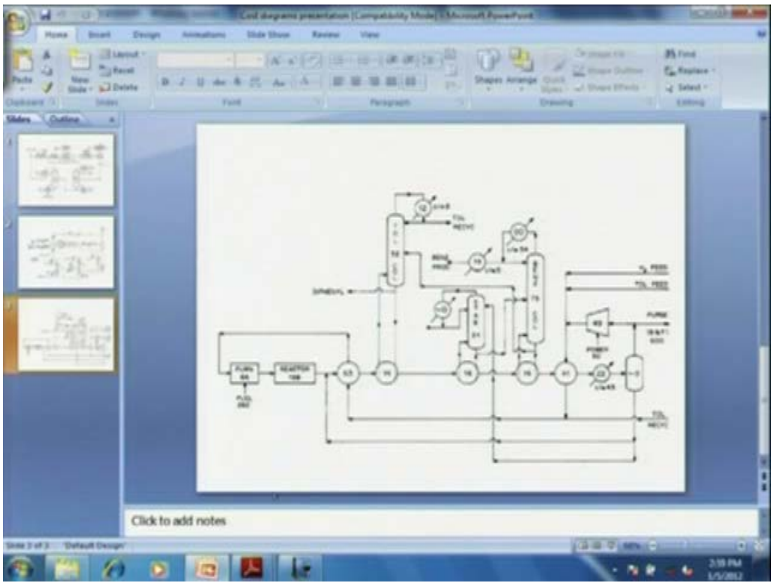
(Refer Slide Time: 03:30)



There after at level 3, the recycle structure of the flow sheet. We had the option of using the single reactor use of the recycle stream for the unreacted reactants. Then the third design variable that we had major design variable that was the molar ratio of the 2 reactants, hydrogen and the aromatics at reactor inlet. Then the recycle gas compressor then the mode of reactor operation whether, aerobatic or isothermal and finally, the equilibrium limited area reactions the shift of equilibrium to favorable sides.

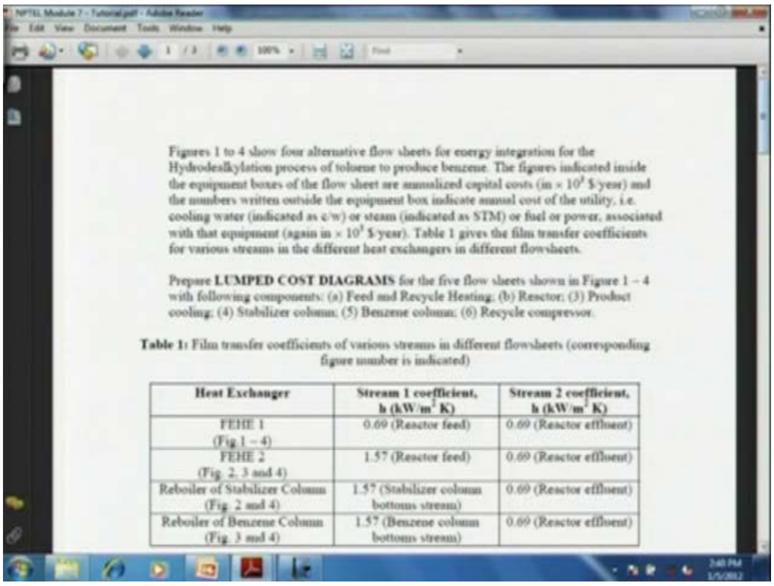
Now, in hydro de alkalization process biphenyl is the reversible products. So, shifting the equilibrium to benzene sides is favorable shift and we saw how we can achieved it or what are the, consequences of recycling biphenyl that are also were assessed in the last lecture. Now, in this lecture, we shall see various energy integrated options of the hydro de alkalization processes.

(Refer Slide Time: 04:33)



What we saw in previous lectures, as just one option that you see on the screen, now. But, there could be many, many alternatives and today, we shall analyst the cost diagrams of these energy alternatives and more over we shall also prepare cost location diagram for one of this alternatives. So, let us see the first problems the problem of preparing the cost diagram for different energy alternatives.

(Refer Slide Time: 05:00)



Figures 1 to 4 show four alternative flow sheets for energy integration for the Hydrodealkylation process of toluene to produce benzene. The figures indicated inside the equipment boxes of the flow sheet are annualized capital costs (in $\times 10^3$ \$/year) and the numbers written outside the equipment box indicate annual cost of the utility, i.e. cooling water (indicated as c/w) or steam (indicated as STM) or fuel or power, associated with that equipment (again in $\times 10^3$ \$/year). Table 1 gives the film transfer coefficients for various streams in the different heat exchangers in different flowsheets.

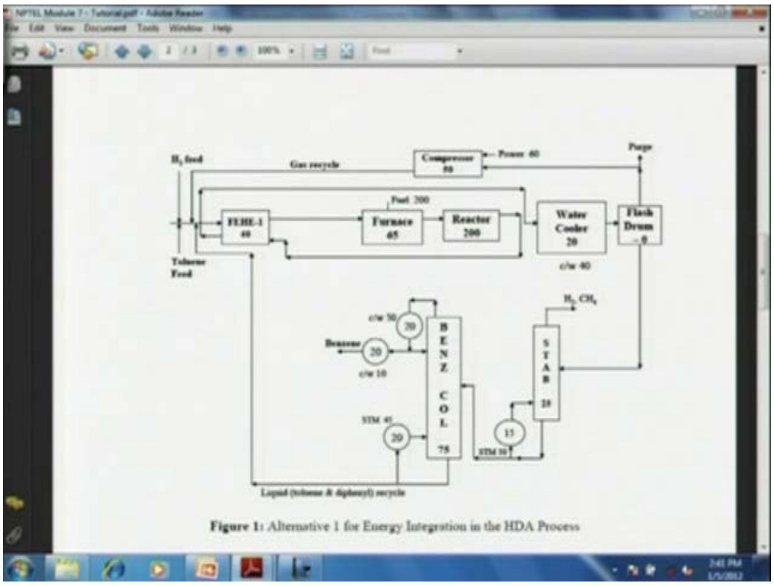
Prepare **LUMPED COST DIAGRAMS** for the five flow sheets shown in Figure 1 – 4 with following components: (a) Feed and Recycle Heating; (b) Reactor; (3) Product cooling; (4) Stabilizer column; (5) Benzene column; (6) Recycle compressor.

Table 1: Film transfer coefficients of various streams in different flowsheets (corresponding figure number is indicated)

Heat Exchanger	Stream 1 coefficient, h ($kW/m^2 K$)	Stream 2 coefficient, h ($kW/m^2 K$)
FEHE 1 (Fig.1 – 4)	0.69 (Reactor feed)	0.69 (Reactor effluent)
FEHE 2 (Fig. 2, 3 and 4)	1.57 (Reactor feed)	0.69 (Reactor effluent)
Reboiler of Stabilizer Column (Fig. 2 and 4)	1.57 (Stabilizer column bottoms stream)	0.69 (Reactor effluent)
Reboiler of Benzene Column (Fig. 3 and 4)	1.57 (Benzene column bottoms stream)	0.69 (Reactor effluent)

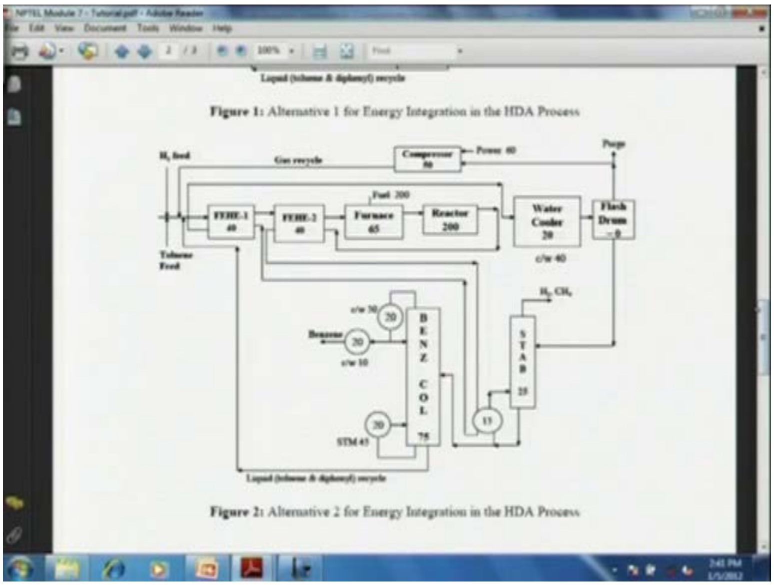
We are given 4 figures that show alternative flow sheet for energy integration for hydro de alkalization process, to hydro de alkalization process of toluene to produce benzene, the figures integrated inside the equipment boxes of the flow sheet are annualized capital cost in 1000 dollars per year. And then numbers written outside the equipment box indicate the annual cost of the utility, that is cooling water that we have indicated as the c oblic w or steel indicated as STM or fuel for the furnace or power for the compressor associated with each of that particular equipment. And the operating cost is also in 1000 dollar per year. We are given a table that give the film transfer coefficients of various streams in the different flow sheet, corresponding to the figure number let us first see, the flow sheets that we have.

(Refer Slide Time: 05:54)



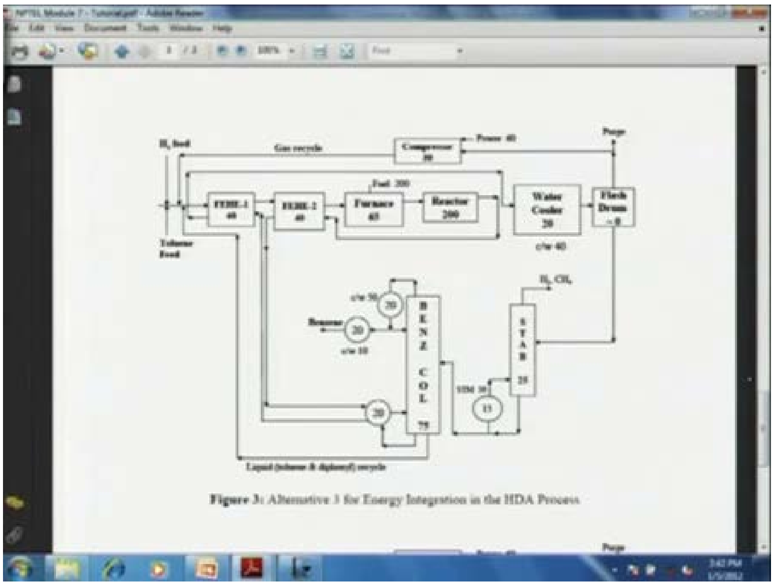
The first low sheet is that you have in screen. Here we have the reactor the effluent stream then effluent stream first passes through FEHE feed to effluent exchanger there after, it goes to water cooler. So, here we have only 1 FEHE, and then the fresh feed is heated through a FEHE and furnace. Here, we see the recycle of toluene and biphenyl. So, there are only 2 columns, and what you see are the numbers corresponding to the annual capital cost.

(Refer Slide Time: 06:25)



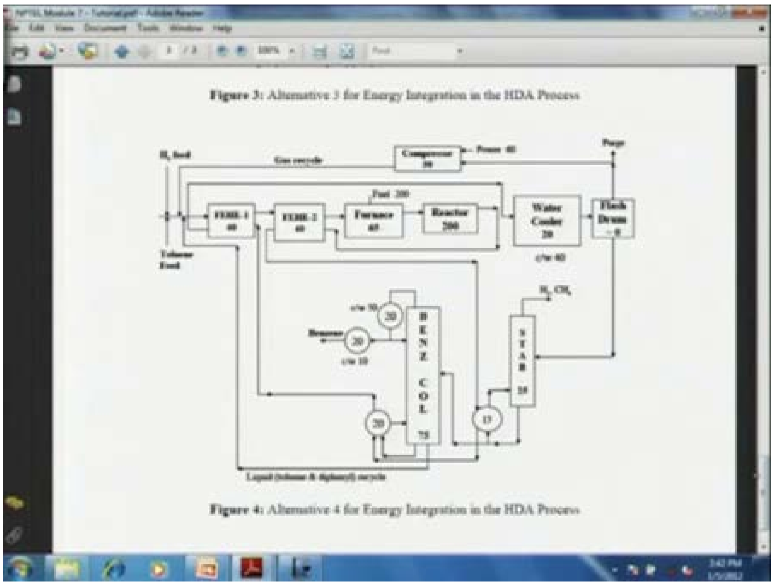
Then the second alternative, in the second alternative there are 2 heat effluent heat exchangers, the effluent stream from the reactor enter the first second exchanger first then it drives the re boiler column of the stabilizer column sorry it drives the re boiler to the stabilizer column then it enters to a first feed to effluent exchanger thereafter, it enters the final water cooler and thereafter the flash drum. The feed and recycle hydrogen toluene are heated through the 2 exchangers as well as the furnace. That is the second alternative for the energy integrated flow sheet.

(Refer Slide Time: 07:11)



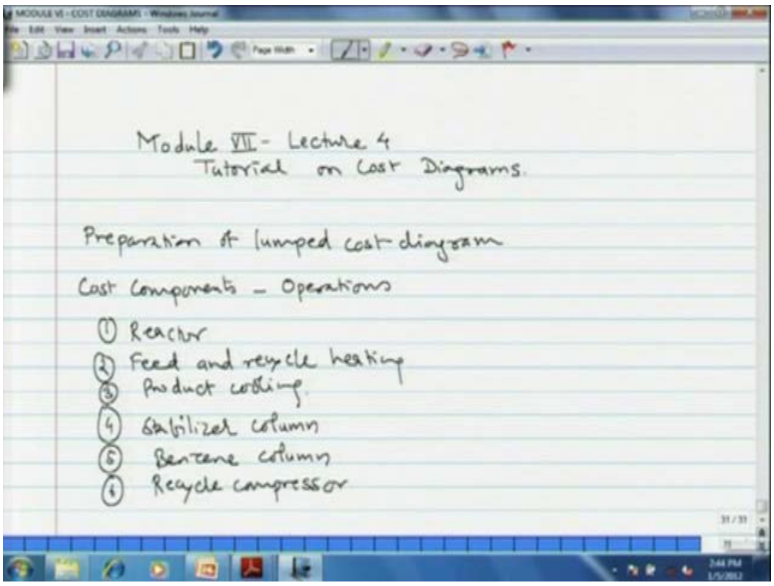
The third alternative is now, on your screen here, we see that the benzene column re boiler is being driven by the reactor effluent the stabilizer column has been given separate stream for the re boiler, the rest of the flow sheet is more or less similar.

(Refer Slide Time: 07:33)



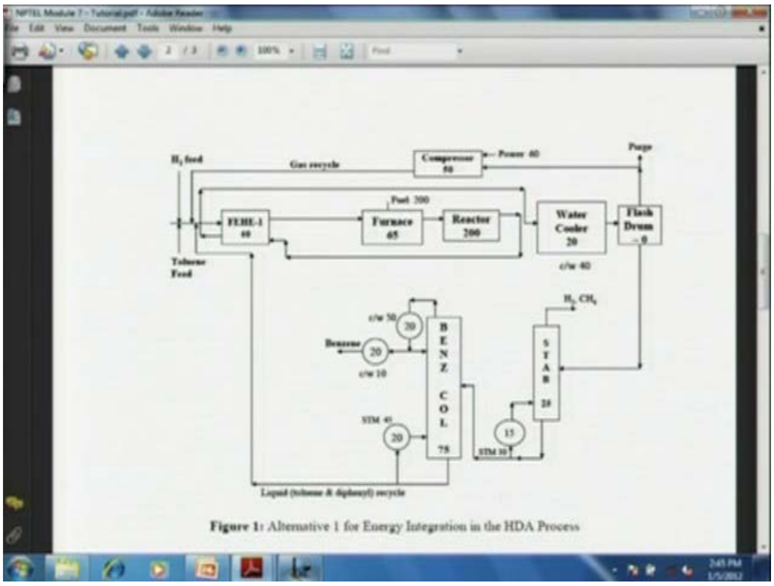
And finally, fourth integrated flow sheet is that the reactor effluent first enters the second FEHE there after it drives to the re boiler of stabilizer column there after, it drives to the re boiler benzene column there after, it goes into FEHE one the first feed to effluent heat exchanger and finally, into water cooler. So, we have to prepare the lumped cost diagram or these 4 flow sheets. And we are give the film transfer coefficient for each of the streams.

(Refer Slide Time: 08:10)



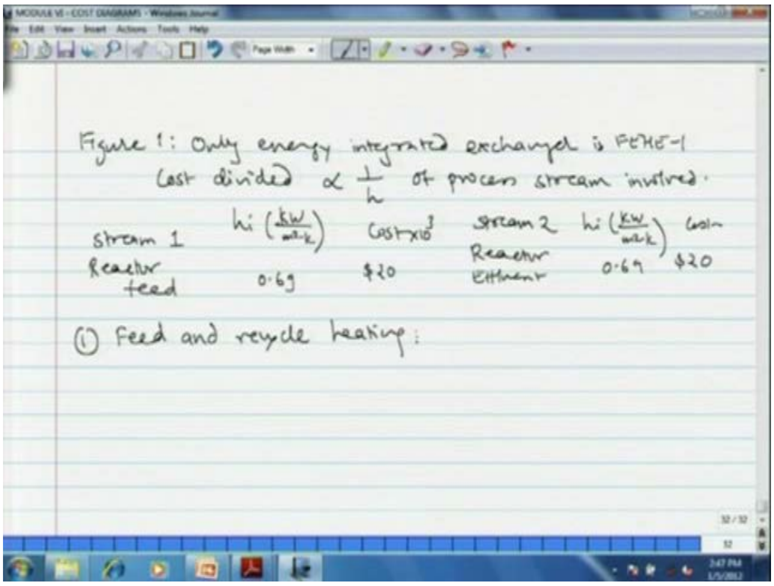
Now, let us start with first flow sheet. Preparation of lumped cost diagram, the operation that we have cost components or the operations for which we will list the cost are first the reactor then the feed and recycle heating, the product cooling then the 2 columns and finally, the gas recycle or recycler compressor. So, these are our cost components and we shall now, lumped the cost for each of these components let us start with figure.

(Refer Slide Time: 09:53)



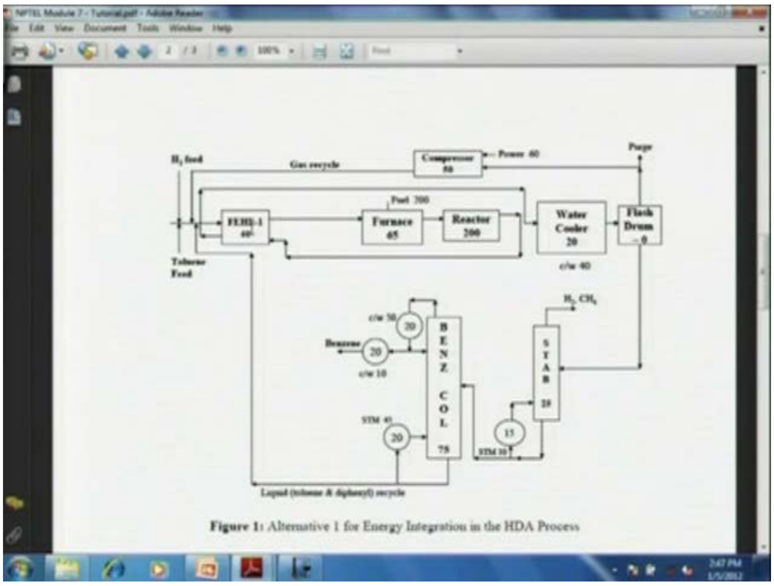
Here we have only one heat exchanger whose capital cost we have to distribute between, the 2 streams that is heating stream. Stream 1 is the reactor feed and stream 2 is reactor effluent, we are given the heat transfer co efficient as 0.69 kilo watt temperature kilo per meter Calvin for reactor feed and again 0.69 kilo watt per meter square kilo per Calvin for reactor effluent, we have to distribute that cost. And since, the co efficient are same the cost will be distributed equally.

(Refer Slide Time: 10:33)



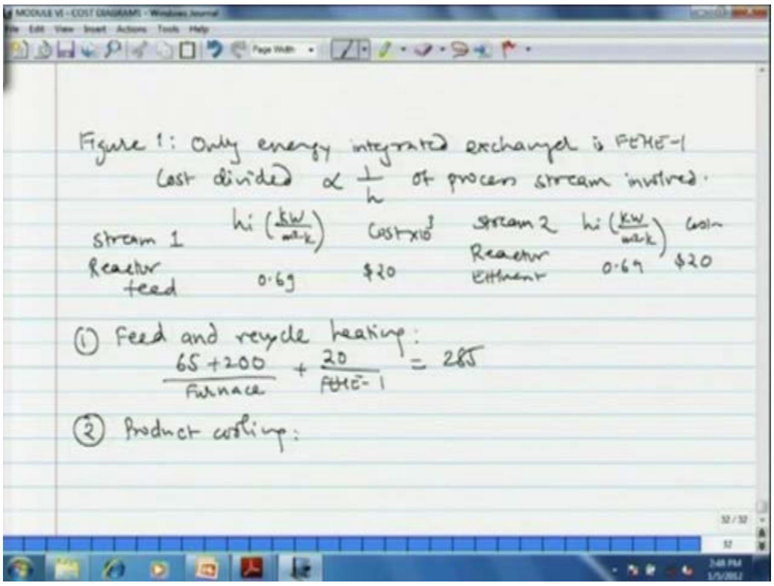
That point we note, figure 1, only energy integrated exchanger is FEHE 1 cost divided in proportion of inverse of the film co efficient that we denote by h of the process stream involved in it. Stream in the exchanger is reactor feed the co efficient h i is 0.69 kilo watt per meter kilo square Calvin. Then the second stream 2 is reactor effluent the film co efficient is 0.69 and the cost is divided half in 10,000 dollars. So, with that we collect the cost associated with each of the given component first the feed and recycle heating.

(Refer Slide Time: 12:27)



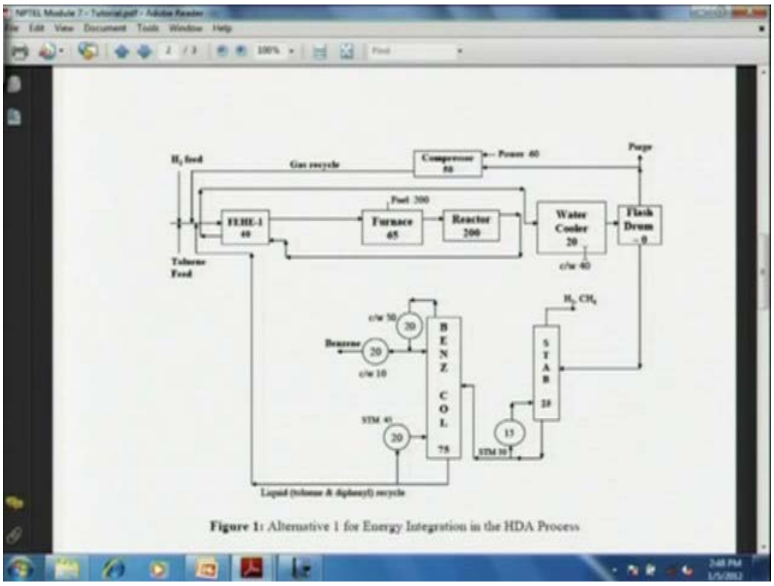
Feed recycle heating takes place through FEHE 1 and the furnace. So, those 2 things we add.

(Refer Slide Time: 12:32)



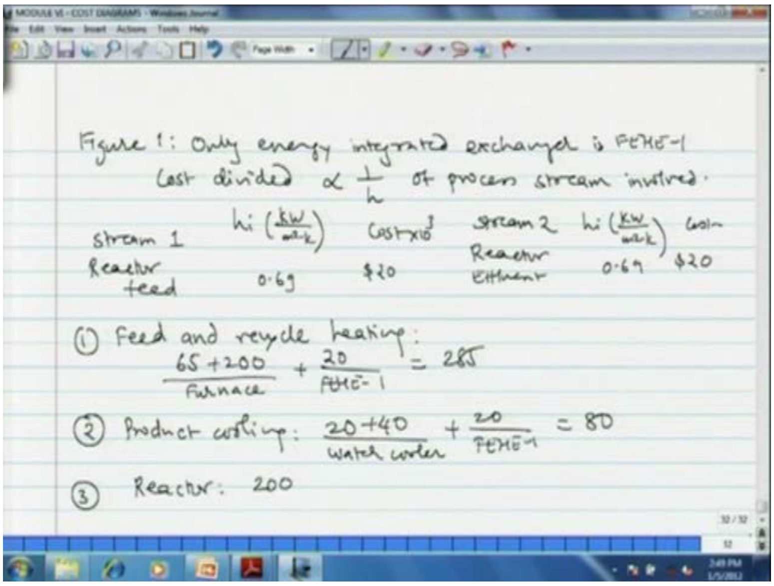
The furnace cost 65 plus 200 fixed cost and operating cost plus the portion of FEHE and the total cost is thus 285. Then the product cooling occurs to.

(Refer Slide Time: 13:08)



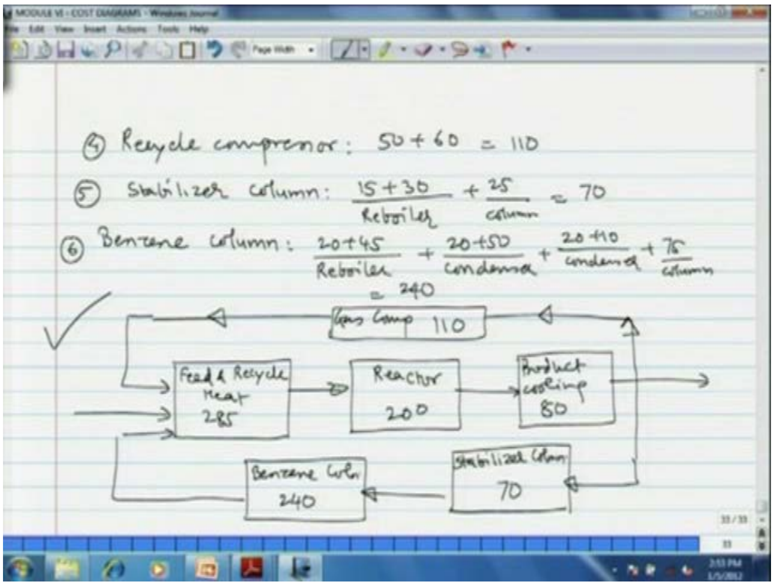
Through FEHE one as well as the condenser has the annual capital cost 20000 dollars and cooling watt of cost 40000.

(Refer Slide Time: 13:16)



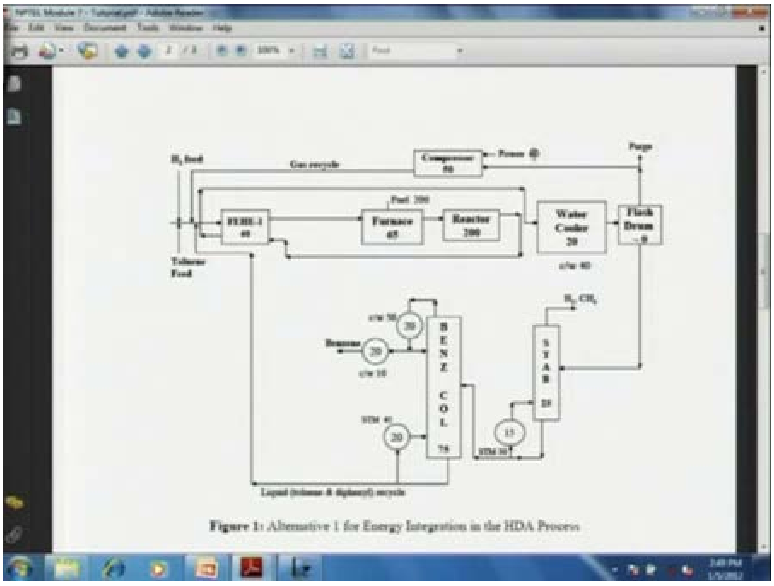
So, those two things we had. 20 plus 40 for water cooler plus the portion of FEHE 1 and then the total is 80 then the third is the reactor has the total cost 200 that we take as it is.

(Refer Slide Time: 13:50)



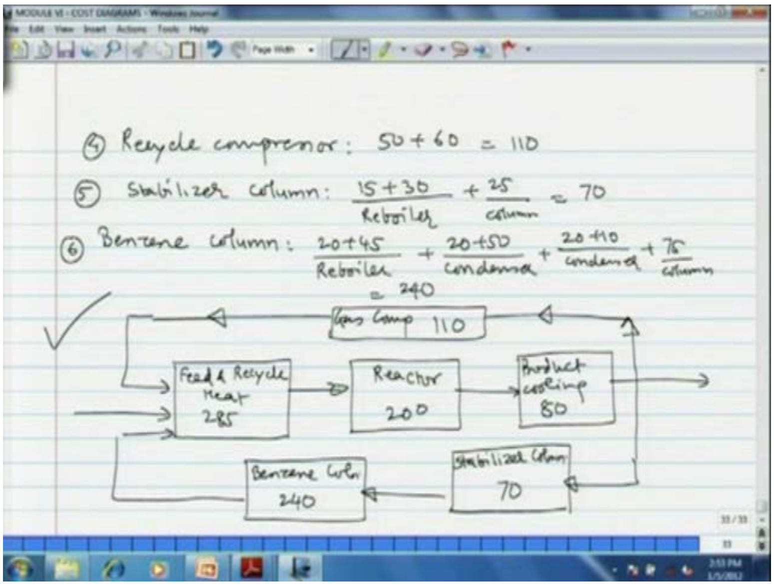
Then the recycle compressor.

(Refer Slide Time: 14:11)



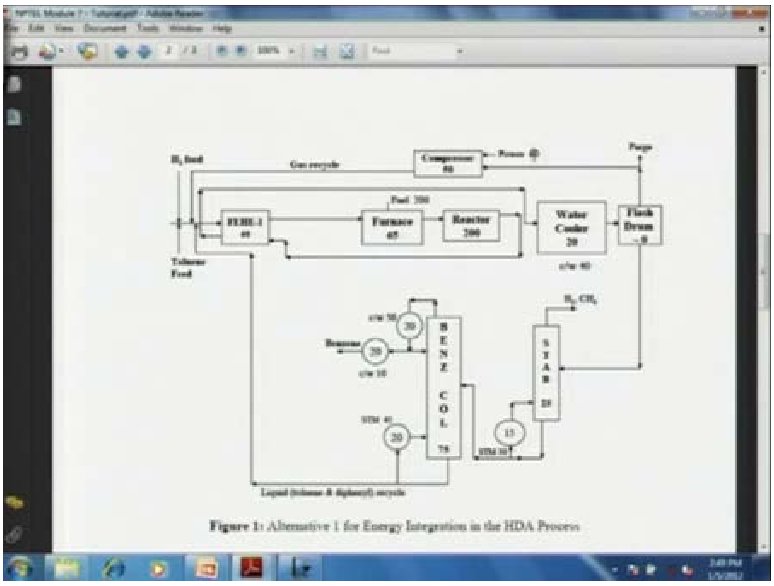
Has the 50,000 dollars as the annualized capital cost and 60,000 dollar of power.

(Refer Slide Time: 14:17)



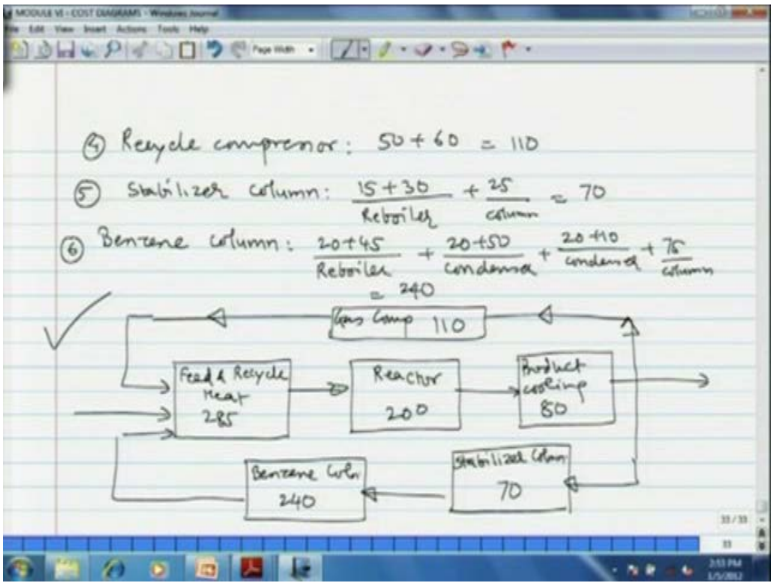
So, those two thing add 50 plus 60 110 then the stabilizer column for the re boiler.

(Refer Slide Time: 14:44)



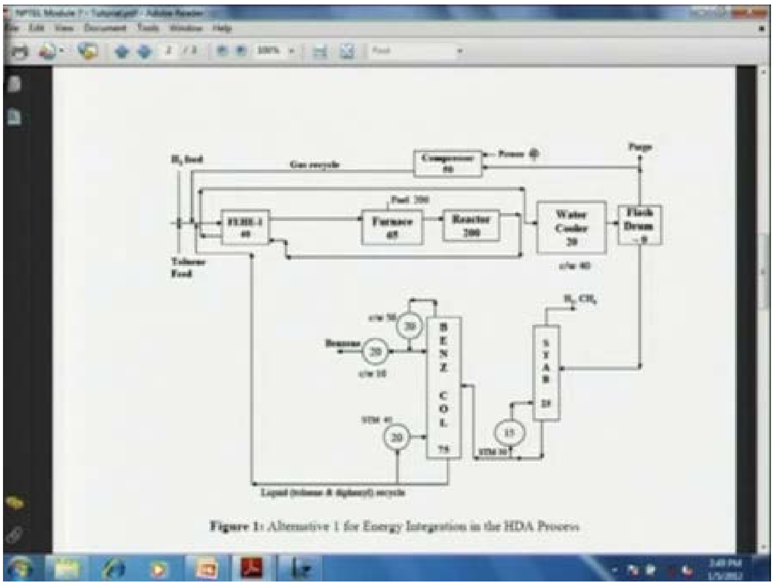
15 for the 50,000 dollar has the annual capital cost of the re boiler and 30,000 dollar stream required.

(Refer Slide Time: 14:53)



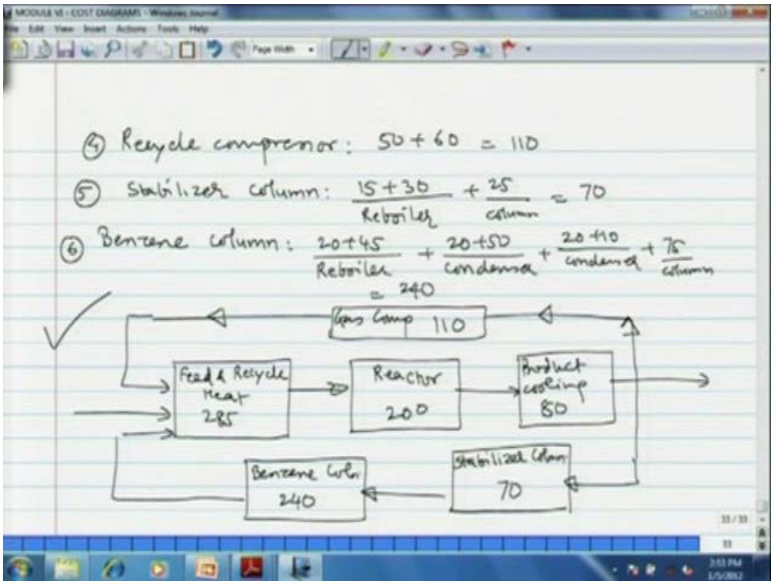
And then the cost of column itself 25,000 dollars. So, these add up to 70,000. Then benzene column 20 plus 45 for the re boiler.

(Refer Slide Time: 15:20)



Then 20 plus 50 and 20 plus 10 for the 2 condenser and 75,000 for column itself.

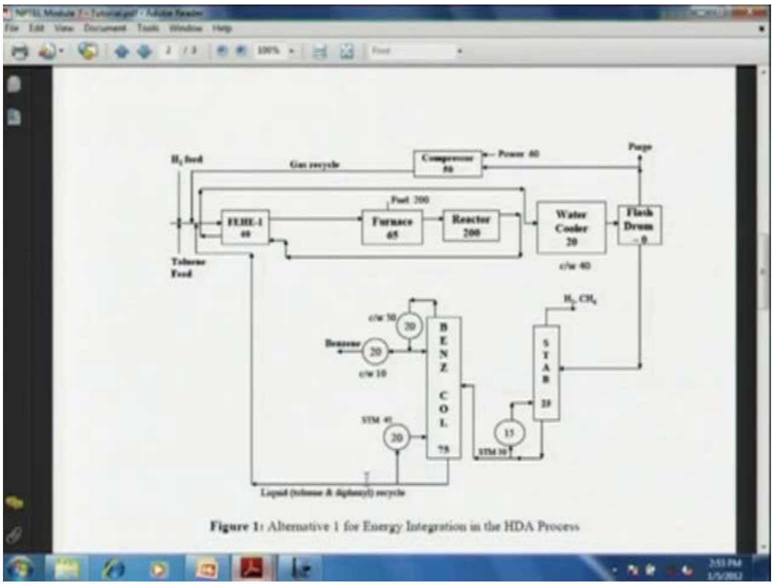
(Refer Slide Time: 15:20)



This together comes out to be 240. And then if you put all this numbers in the boxes, we get lumped cost diagram for that particular flow sheet. We are now, connecting these boxes each boxes integrate the particular operation, now we have not given any information about the cost of recycle purge. So, that it is not indicated here, we are now putting different numbers 2,00,000 dollar capital cost the annualized capital cost reactor 100 and 10,000 dollar per gas compression 2,25,000 dollar for feed and recycle heating

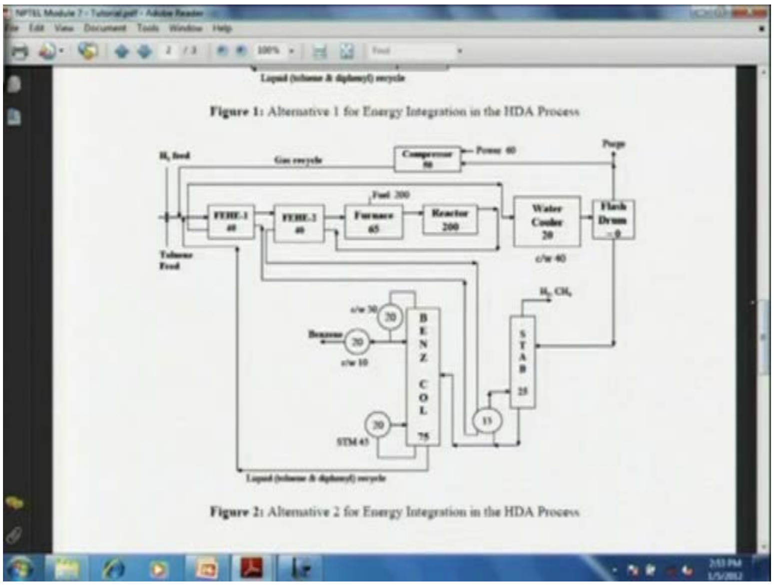
2,40,000 dollars for benzene column 70,000 dollars for stabilizer column and 80,000 dollar for product cooling. And this completes our lumped cost diagram for process alternative 1. Now, we can proceed similar way for other diagrams now, I will do a bit fast because I have already explained in detail we have to follow the similar procedure for the other flow sheets. Now, let us take flow sheet 2, in flow sheet 2 we have 3 energy integrations exchangers.

(Refer Slide Time: 18:31)



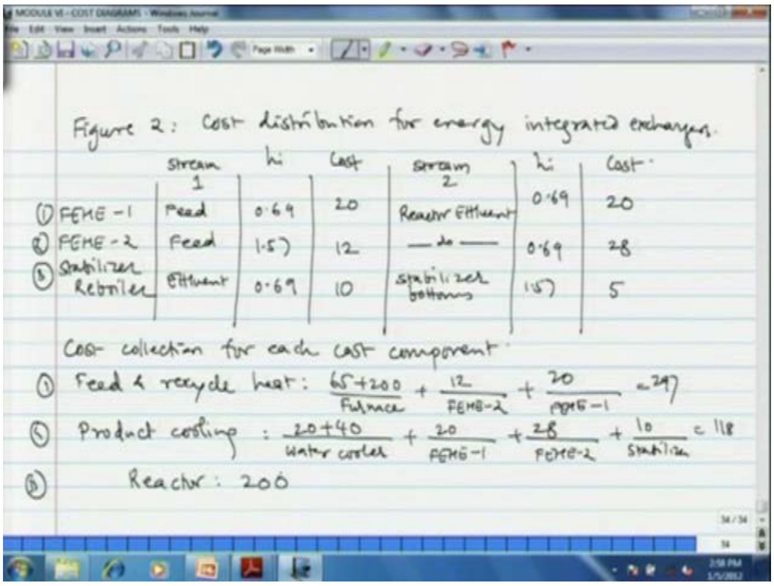
FEHE 1 then FEHE 2.

(Refer Slide Time: 18:38)



The re boiler of step laser column. So, we have to distribute the cost according to the film co efficient of the streams that are involved in each of these 3 exchangers.

(Refer Slide Time: 18:55)

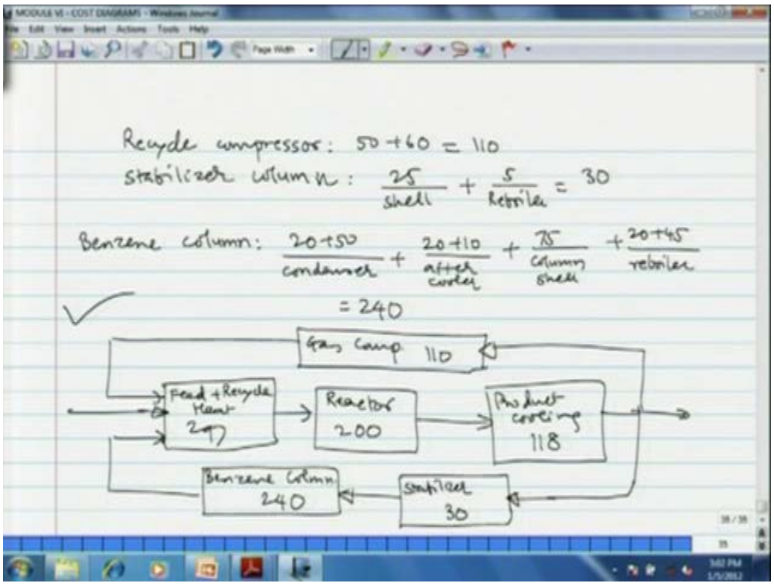


So, that point we note now, figure 2 cost distribution for energy integrated exchangers FEHE 1 FEHE 2 and stabilizer re boiler. And then the streams involved feed, a effluent reactor effluent then we are given the h i heat transfer co efficient 0.69, 1.57, 0.69 then the allocated cost then stream 2 for FEHE 1 stream 2 is reactor fluent. Second now, also reactor fluent and for the third it is stabilizer bottom the film coefficients are 0.69, 0.69 1.57and then the cost.

The total cost of FEHE 1 is 40,000 dollars less capital cost. Since, the 2 coefficient are same we distribute equally then for the second FEHE 2 the total cost is again 40 but stream coefficients are not same feed has higher coefficient. So, lesser cost and that we have already seen how to do it is in inverse proportion of h i. So, now, I write directly the answer you can very easily calculate yourself. Low coefficient high cost 1.1 divided by 0.69 divided by 1 divided 0.69 plus 1 divided by 1.57 into 40, is what is 28. Similarly, for stabilizer the column the total analyze capital is 15,000 dollars that is distributed in inverse proportion of film coefficients, high film co efficient low cost. So, 0.69 1.57 is gives the distribution 5 and 10.

Now, having done this we now, collect the cost associated with each of the operation cost collection for each cost component. Now, I am giving directly the answer you can verify yourself feed and recycle heating 65 plus 200 furnace plus 12 FEHE 2 plus 20 FEHE 1 total 2, 97,000 dollars. And second product cooling 20 plus 40 for the water cooler plus 20 for FEHE 1 plus 28 for FEHE 2 plus 10 for stabilizer re boiler, together it adds up to 118. Next the reactor here, we do not have any allocation. So, direct 200 dollars.

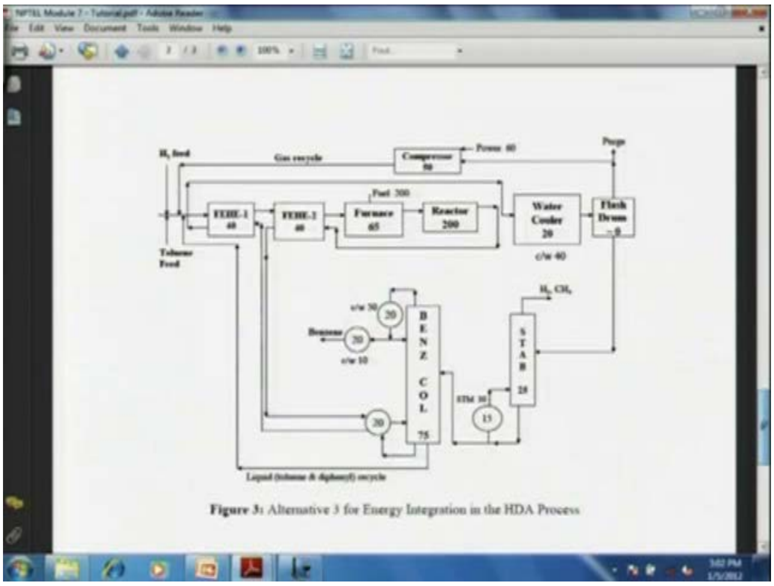
(Refer Slide Time: 23:32)



Then the next one is the recycle compressor, here also the cost remains the same as the previous flow sheet and there is no future distribution 50 plus 60 50,000 dollars annualized capital cost 60,000 dollar power. So, total 110,000 dollars stabilizer column 25,000 dollars for the shell that is the mean body plus the plates and 5000 dollars for re boiler. So, total 30. And then benzene column 20 plus 50 for condenser plus 20 plus 10 the after cooler plus 75 for column shell plus 20 plus 45 for the re boiler and then total gives 240.

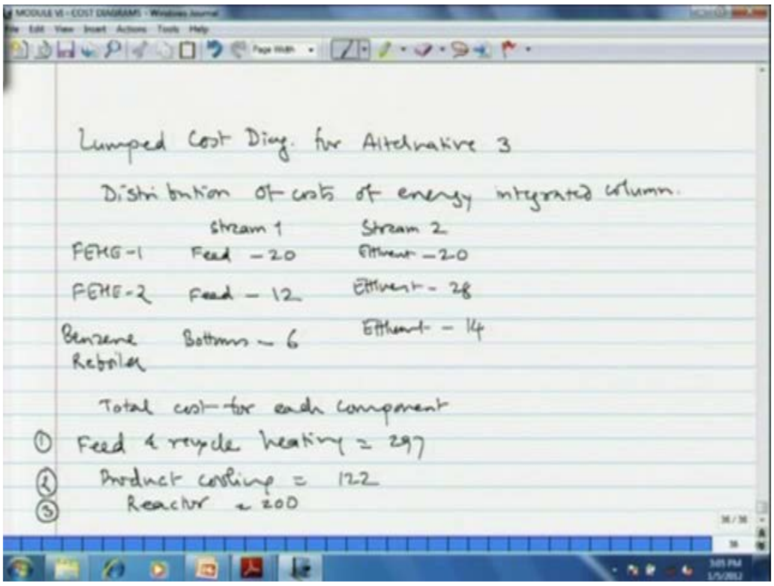
Now, we put all this cost in boxes and then connect them to make the final diagram. Reactor, gas compressor feed plus recycle heat, product cooling, stabilizer, benzene column and then we join these things. And now, we put number reactor 200, feed recycle heat 297, gas compression 110, product cooling 100, and 18 stabilizer column 30 and benzene column 240. And this completes our cost sorry the lumped cost diagram for the second alternative. Now, I will give the answer directly for the third and fourth and I leave it as an exercise for you to solve.

(Refer Slide Time: 27:14)



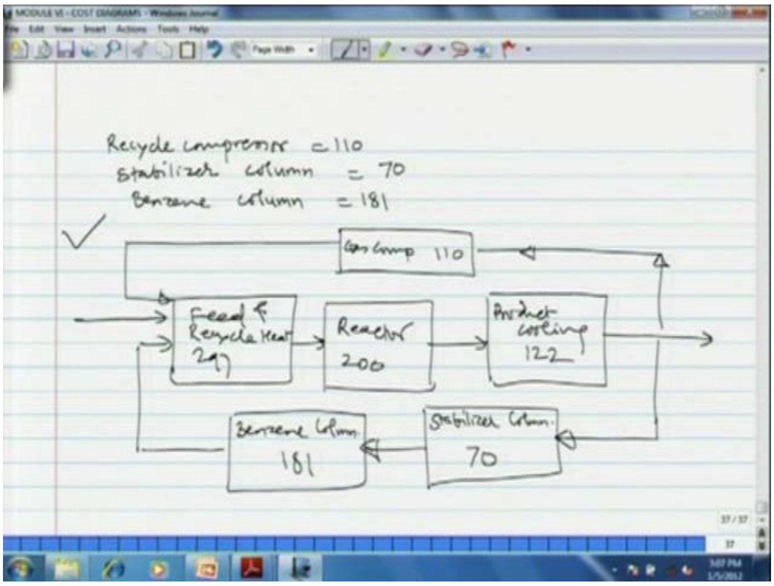
Now, let me briefly give the description here we have in the third alternative we have 2 exchangers. So, we have to distribute the cost of the 2 exchangers plus the benzene re boiler now.

(Refer Slide Time: 27:32)



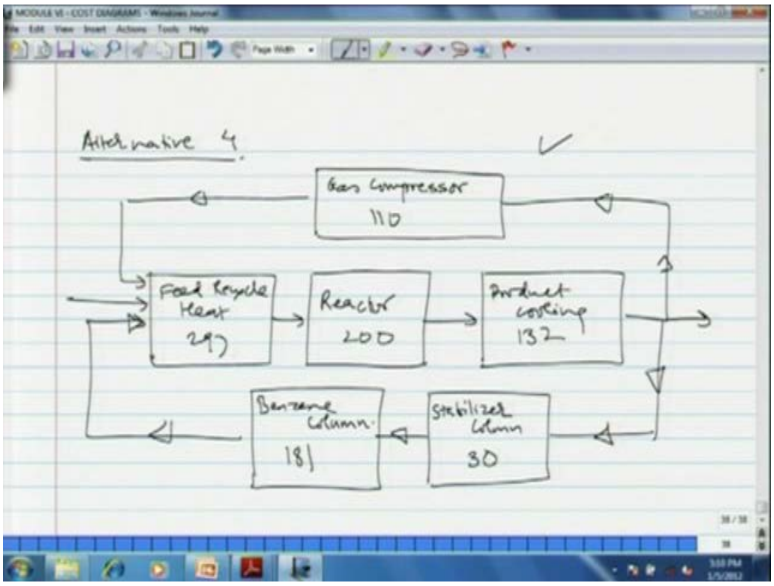
We first see the distribution of cost of energy integrated column FEHE 1, FEHE 2 and benzene re boiler and now I directly give the cost total cost 40 40 and 20. So, that is distributed among stream 1 and stream 2 feed 20 feed 12 bottoms 6 stream 2 a effluent 20 stream 2 is effluent reactor effluent in all 3 cases. So, for FEHE 1 20,000 dollar is the share of effluent. FEHE 2 28,000 dollar is the share of effluent and benzene re boiler 14,000 dollar is the share of effluent. Now, having distributed this the total cost for each component or operation I directly give the final figure I leave the exact break up to you, feed recycle heating 2,970,000 dollars product cooling 1,22,000 dollars reactor 200.

(Refer Slide Time: 30:12)



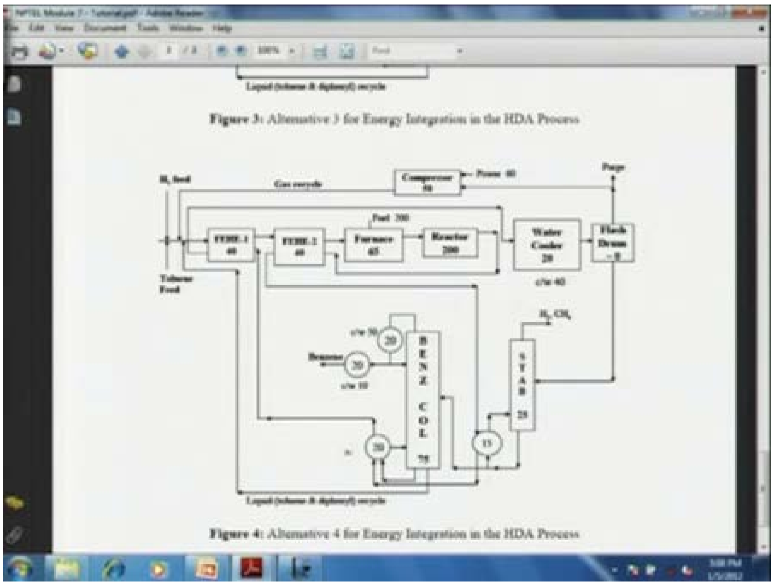
Then the recycle compressor 110, stabilizer columns 70 and benzene column 181. And same thing in block diagram and now we put the numbers inside gas compression 110, stabilizer columns 70, benzene column 18,1 feed and recycle heat 297, reactor 200 and product cooling 122. So, this give the lumped cost diagram for energy integrated flow sheet 3 or process alternative 3, for the fourth one I am directly going to give lumped cost diagram.

(Refer Slide Time: 32:17)



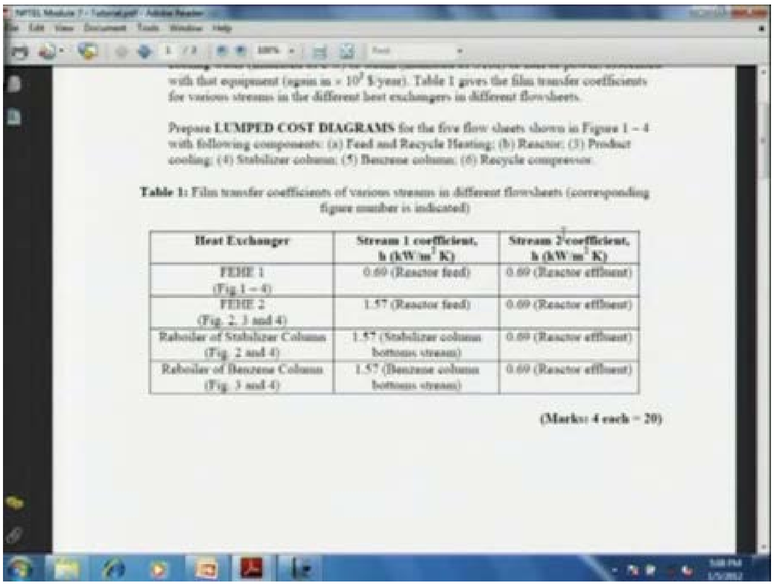
In fourth alternative we have 4 exchange integrated FEHE 1, FEHE 2.

(Refer Slide Time: 32:39)



Then re boilers of both columns. So, we have to distribute the cost you have been given the film co efficient in the table.

(Refer Slide Time: 32:51)



with that equipment (again in × 10^3 \$/year). Table 1 gives the film transfer coefficients for various streams in the different heat exchangers in different flowsheets.

Prepare **LUMPED COST DIAGRAMS** for the five flow sheets shown in Figure 1 – 4 with following components: (a) Feed and Recycle Heating; (b) Reactor; (3) Product cooling; (4) Stabilizer column; (5) Benzene column; (6) Recycle compressor.

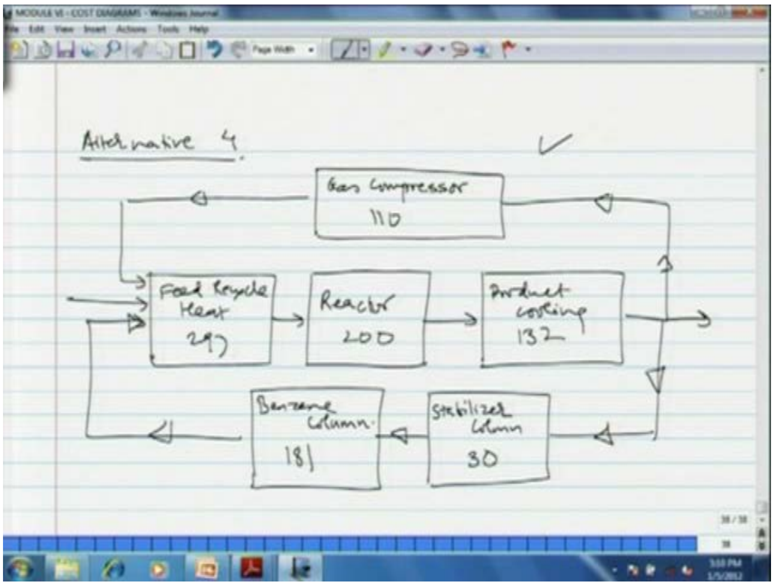
Table 1: Film transfer coefficients of various streams in different flowsheets (corresponding figure number is indicated)

Heat Exchanger	Stream 1 coefficient, h ($kW/m^2 K$)	Stream 2 coefficient, h ($kW/m^2 K$)
FEHE 1 (Fig 1 – 4)	0.69 (Reactor feed)	0.69 (Reactor effluent)
FEHE 2 (Fig. 2, 3 and 4)	1.57 (Reactor feed)	0.69 (Reactor effluent)
Reboiler of Stabilizer Column (Fig. 2 and 4)	1.57 (Stabilizer column bottoms stream)	0.69 (Reactor effluent)
Reboiler of Benzene Column (Fig. 3 and 4)	1.57 (Benzene column bottoms stream)	0.69 (Reactor effluent)

(Marks: 4 each = 20)

We have given film co efficient in the table FEHE 1 etcetera re boiler of benzene column re boiler of toluene column now, you distribute the cost and then finally, you can obtain lumped cost diagram as follows.

(Refer Slide Time: 33:05)



Reactor 200, product cooling 132, feed recycle heat 297, gas recycle compression 110, benzene column 181 and stabilizer column 30. So, this energy sorry the elm cost diagram for the process alternative 4. So, that completes our first part of our tutorial. Now, we have to go future for preparation of cost allocation diagram. Now, as I mentioned in previous lecture cost location diagram is prepared from the lumped cost diagram by allocating the cost elm, cost component reactor and product cooling and feed recycling to the 3 steam that are involved in that particular operation or component. And the 3 steam are net fresh feed, gas recycle and liquid recycle. Now, we shall try to prepare the cost allocation diagram for the alternative 2.

(Refer Slide Time: 35:30)

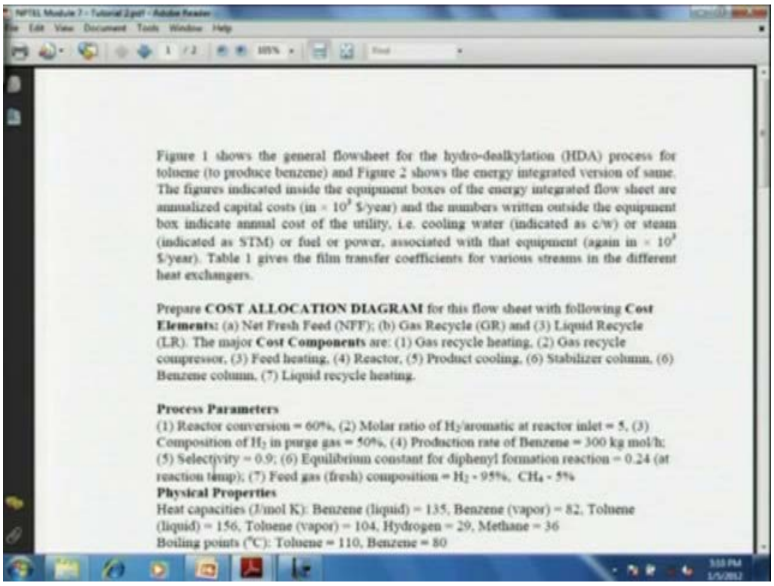


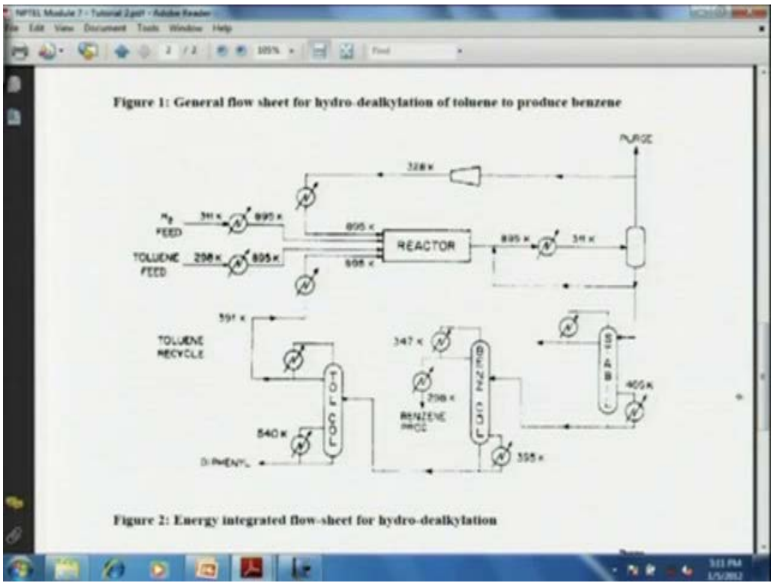
Figure 1 shows the general flowsheet for the hydro-dealkylation (HDA) process for toluene (to produce benzene) and Figure 2 shows the energy integrated version of same. The figures indicated inside the equipment boxes of the energy integrated flow sheet are annualized capital costs (in × 10^3 \$/year) and the numbers written outside the equipment box indicate annual cost of the utility, i.e. cooling water (indicated as c/w) or steam (indicated as STM) or fuel or power, associated with that equipment (again in × 10^3 \$/year). Table 1 gives the film transfer coefficients for various streams in the different heat exchangers.

Prepare **COST ALLOCATION DIAGRAM** for this flow sheet with following **Cost Elements:** (a) Net Fresh Feed (NFF); (b) Gas Recycle (GR) and (3) Liquid Recycle (LR). The major **Cost Components** are: (1) Gas recycle heating, (2) Gas recycle compressor, (3) Feed heating, (4) Reactor, (5) Product cooling, (6) Stabilizer column, (6) Benzene column, (7) Liquid recycle heating.

Process Parameters
(1) Reactor conversion = 60%, (2) Molar ratio of H_2/aromatic at reactor inlet = 5, (3) Composition of H_2 in purge gas = 50%, (4) Production rate of Benzene = 300 kg mol/h; (5) Selectivity = 0.9; (6) Equilibrium constant for diphenyl formation reaction = 0.24 (at reaction temp); (7) Feed gas (fresh) composition = H_2 - 95%, CH_4 - 5%
Physical Properties
Heat capacities (J/mol K): Benzene (liquid) = 135, Benzene (vapor) = 82, Toluene (liquid) = 156, Toluene (vapor) = 104, Hydrogen = 29, Methane = 36
Boiling points (°C): Toluene = 110, Benzene = 80

Now, we need some more information for that which now, appears on your screen this is the second problem of tutorial figure 1 shows the general flow sheet of hydro de alkalization process.

(Refer Slide Time: 35:49)



This we have seen several times before this is general flow sheet indicating various temperatures and flow of the steams.

(Refer Slide Time: 35:57)

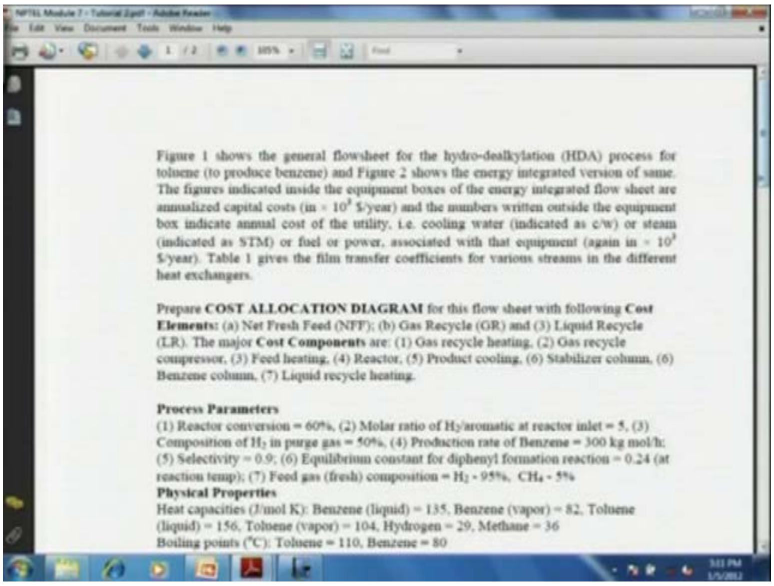


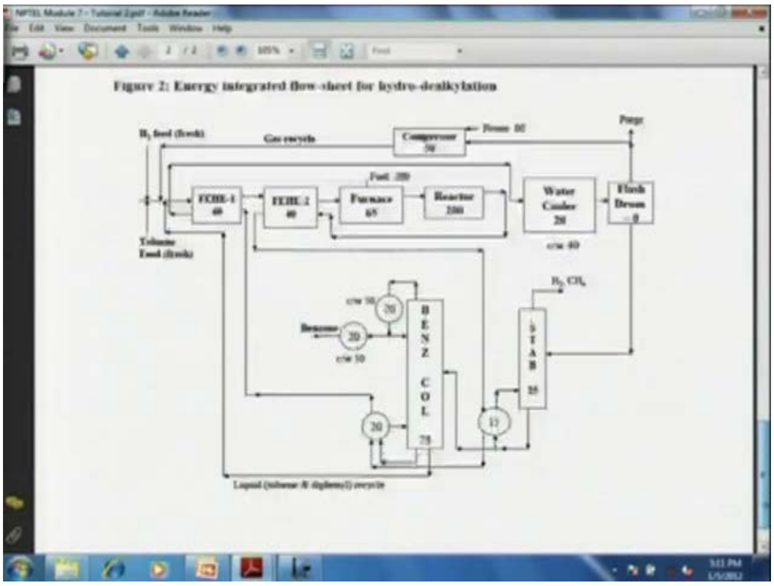
Figure 1 shows the general flowsheet for the hydro-dealkylation (HDA) process for toluene (to produce benzene) and Figure 2 shows the energy integrated version of same. The figures indicated inside the equipment boxes of the energy integrated flow sheet are annualized capital costs (in × 10^3 \$/year) and the numbers written outside the equipment box indicate annual cost of the utility, i.e. cooling water (indicated as c/w) or steam (indicated as STM) or fuel or power, associated with that equipment (again in × 10^3 \$/year). Table 1 gives the film transfer coefficients for various streams in the different heat exchangers.

Prepare **COST ALLOCATION DIAGRAM** for this flow sheet with following **Cost Elements:** (a) Net Fresh Feed (NFF); (b) Gas Recycle (GR) and (3) Liquid Recycle (LR). The major **Cost Components** are: (1) Gas recycle heating, (2) Gas recycle compressor, (3) Feed heating, (4) Reactor, (5) Product cooling, (6) Stabilizer column, (6) Benzene column, (7) Liquid recycle heating.

Process Parameters
(1) Reactor conversion = 60%, (2) Molar ratio of H_2/aromatic at reactor inlet = 5, (3) Composition of H_2 in purge gas = 50%, (4) Production rate of Benzene = 300 kg mol/h; (5) Selectivity = 0.9; (6) Equilibrium constant for diphenyl formation reaction = 0.24 (at reaction temp); (7) Feed gas (fresh) composition = H_2 - 95%, CH_4 - 5%
Physical Properties
Heat capacities (J/mol K): Benzene (liquid) = 135, Benzene (vapor) = 82, Toluene (liquid) = 156, Toluene (vapor) = 104, Hydrogen = 29, Methane = 36
Boiling points (°C): Toluene = 110, Benzene = 80

Figure 2 shows the energy integrated origin of the same.

(Refer Slide Time: 36:02)



Now, what our process alternative 2 in which we had 2 FEHE and 2 re boiler column sorry 2 re boiler integrated.

(Refer Slide Time: 36:48)

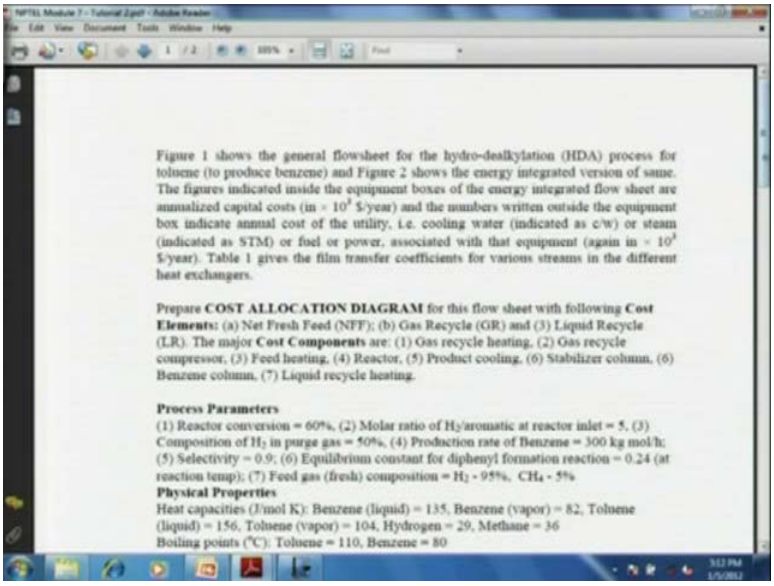


Figure 1 shows the general flowsheet for the hydro-dealkylation (HDA) process for toluene (to produce benzene) and Figure 2 shows the energy integrated version of same. The figures indicated inside the equipment boxes of the energy integrated flow sheet are annualized capital costs (in × 10^3 \$/year) and the numbers written outside the equipment box indicate annual cost of the utility, i.e. cooling water (indicated as c/w) or steam (indicated as STM) or fuel or power, associated with that equipment (again in × 10^3 \$/year). Table 1 gives the film transfer coefficients for various streams in the different heat exchangers.

Prepare **COST ALLOCATION DIAGRAM** for this flow sheet with following **Cost Elements:** (a) Net Fresh Feed (NFF); (b) Gas Recycle (GR) and (3) Liquid Recycle (LR). The major **Cost Components** are: (1) Gas recycle heating, (2) Gas recycle compressor, (3) Feed heating, (4) Reactor, (5) Product cooling, (6) Stabilizer column, (6) Benzene column, (7) Liquid recycle heating.

Process Parameters

(1) Reactor conversion = 60%, (2) Molar ratio of H_2/aromatic at reactor inlet = 5, (3) Composition of H_2 in purge gas = 50%, (4) Production rate of Benzene = 300 kg mol/h; (5) Selectivity = 0.9; (6) Equilibrium constant for diphenyl formation reaction = 0.24 (at reaction temp); (7) Feed gas (fresh) composition = H_2 - 95%, CH_4 - 5%

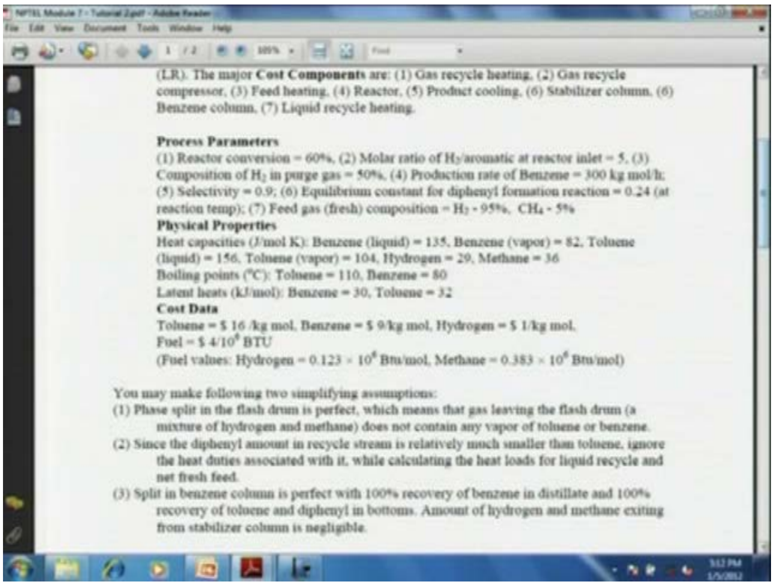
Physical Properties

Heat capacities (J/mol K): Benzene (liquid) = 135, Benzene (vapor) = 82, Toluene (liquid) = 156, Toluene (vapor) = 104, Hydrogen = 29, Methane = 36

Boiling points (°C): Toluene = 110, Benzene = 80

Now, we have to prepare cost allocation diagram. The co efficient remains the same as given earlier in problem one, but; however, we have now, the 3 cost elements, net fresh feed gas recycle and liquid recycle major cost component again are the same as before gas recycling heating, gas recycling compression, feed heating, reactor, product cooling, stabilizer column, benzene column and liquid recycle heating. The process parameters now are.

(Refer Slide Time: 37:21)


(LR). The major **Cost Components** are: (1) Gas recycle heating, (2) Gas recycle compressor, (3) Feed heating, (4) Reactor, (5) Product cooling, (6) Stabilizer column, (6) Benzene column, (7) Liquid recycle heating.

Process Parameters

(1) Reactor conversion = 60%, (2) Molar ratio of H_2/aromatic at reactor inlet = 5, (3) Composition of H_2 in purge gas = 50%, (4) Production rate of Benzene = 300 kg mol/h; (5) Selectivity = 0.9; (6) Equilibrium constant for diphenyl formation reaction = 0.24 (at reaction temp); (7) Feed gas (fresh) composition = H_2 - 95%, CH_4 - 5%

Physical Properties

Heat capacities (J/mol K): Benzene (liquid) = 135, Benzene (vapor) = 82, Toluene (liquid) = 156, Toluene (vapor) = 104, Hydrogen = 29, Methane = 36

Boiling points (°C): Toluene = 110, Benzene = 80

Latent heats (kJ/mol): Benzene = 30, Toluene = 32

Cost Data

Toluene = \$ 16 /kg mol, Benzene = \$ 9/kg mol, Hydrogen = \$ 1/kg mol,

Fuel = \$ 4/10^6 BTU

(Fuel values: Hydrogen = 0.123×10^6 Btu/mol, Methane = 0.383×10^6 Btu/mol)

You may make following two simplifying assumptions:

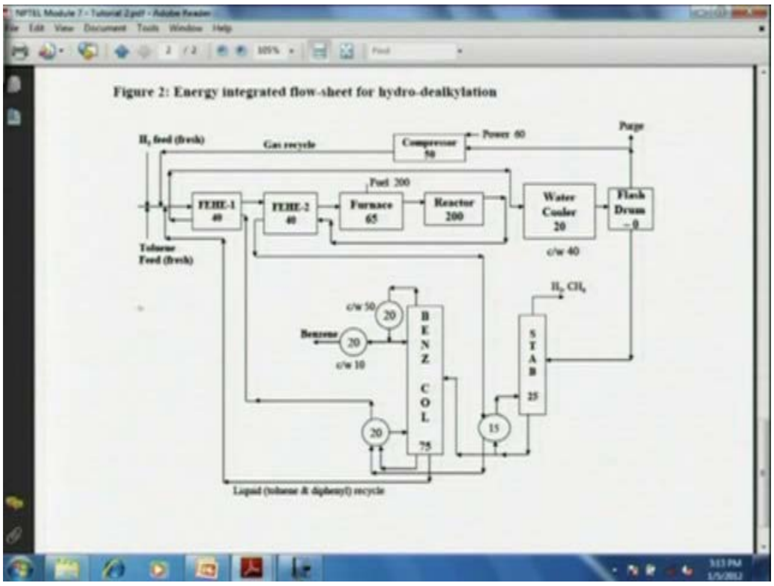
(1) Phase split in the flash drum is perfect, which means that gas leaving the flash drum (a mixture of hydrogen and methane) does not contain any vapor of toluene or benzene.

(2) Since the diphenyl amount in recycle stream is relatively much smaller than toluene, ignore the heat duties associated with it, while calculating the heat loads for liquid recycle and net fresh feed.

(3) Split in benzene column is perfect with 100% recovery of benzene in distillate and 100% recovery of toluene and diphenyl in bottoms. Amount of hydrogen and methane exiting from stabilizer column is negligible.

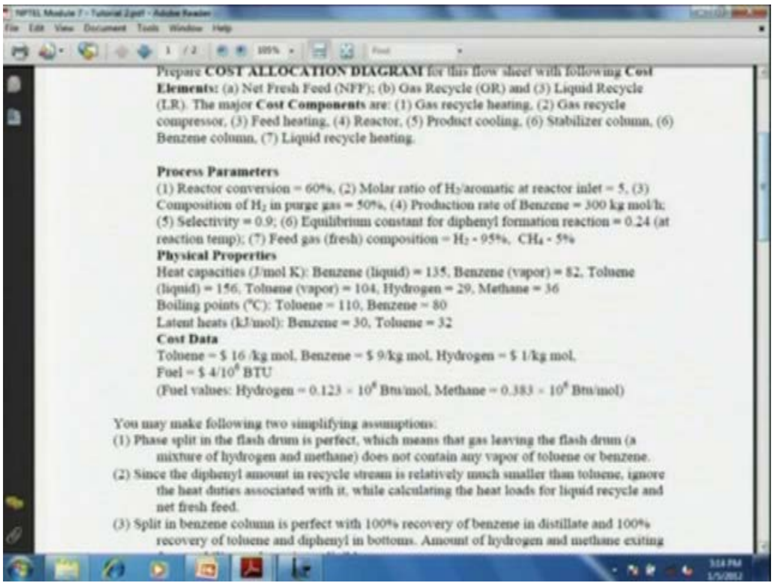
Reactor per pass conversion 60 percent, molar ratio of hydro aromatic set reactor in let 5 composition of hydrogen in purge gas 50 percent, production rate of benzene 300 kilo moles per hour, selectivity at transcend conditions 0.9. However, if you see now, the flow sheet.

(Refer Slide Time: 37:44)



Here you will see that the toluene and biphenyl are recycle to the reactor. Therefore, at steady state the amount of biphenyl in the process remains constant it builds to an equilibrium level and there after it remains constant. And at that condition, at that particular steady state all of the fresh toluene gets converted only to benzene with selectivity equal 1. So, selectivity 0.9 is for transcend condition, steady state selectivity is 1 in case of biphenyl recycle.

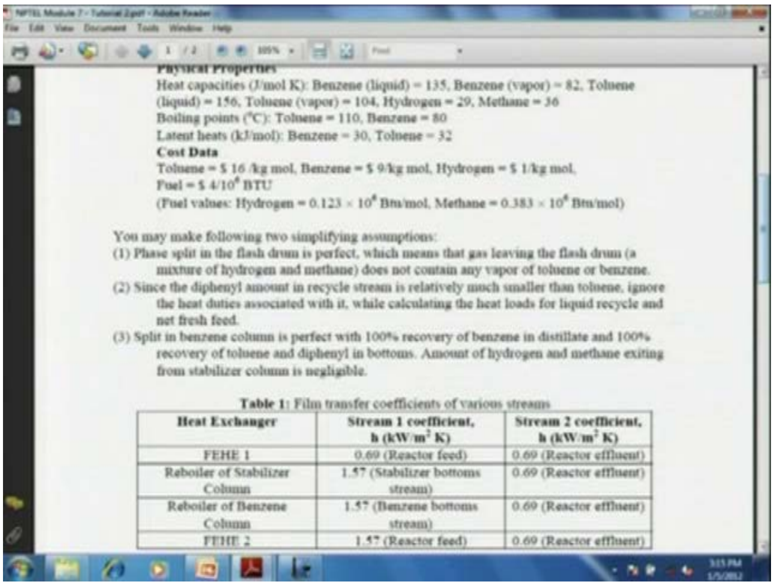
(Refer Slide Time: 38:11)



Then equilibrium cost and for biphenyl formation 0.24 at reaction temperature, feed gas composition, hydrogen 95 percent, methane 5 percent. We are given several physical properties heat capacity in joule per mole per Calvin benzene 135, liquid state benzene vapor 82, toluene liquid 156, toluene vapor 104, hydrogen 29, methane 36, joule per mole per Calvin all of heat capacities, then the boiling points are toluene 110 and benzene 80, latent heats benzene 30, that is in liquid status of course, oh sorry liquid to vapor state the latent heat benzene is 30 kilo joule per mole and toluene is 32 kilo joule per mole.

The heat required for the face transformation from liquid to vapor that is latent heat. Then the cost data, toluene cost has been given as 16 dollars per kg mole, benzene 9 dollar per kg mole, hydrogen 1 dollar per kg mole, fuel cost is 4 dollar 4 per million BTU I have already given the conversion of BTU to kilo joule. And fuel value are hydrogen 0.123 into10 to the power 6 BTU per mole or 0.123 million BTU we can 0.383 million BTU we can we are allowed to give make certain simplify assumptions.

(Refer Slide Time: 39:42)


Physical Properties
Heat capacities (J/mol K): Benzene (liquid) = 135, Benzene (vapor) = 82, Toluene (liquid) = 156, Toluene (vapor) = 104, Hydrogen = 29, Methane = 36
Boiling points (°C): Toluene = 110, Benzene = 80
Latent heats (kJ/mol): Benzene = 30, Toluene = 32
Cost Data
Toluene = $ 16 /kg mol, Benzene = $ 9/kg mol, Hydrogen = $ 1/kg mol,
Fuel = $ 4/10^6 BTU
(Fuel values: Hydrogen = 0.123 × 10^6 Btu/mol, Methane = 0.383 × 10^6 Btu/mol)

You may make following two simplifying assumptions:
(1) Phase split in the flash drum is perfect, which means that gas leaving the flash drum (a mixture of hydrogen and methane) does not contain any vapor of toluene or benzene.
(2) Since the diphenyl amount in recycle stream is relatively much smaller than toluene, ignore the heat duties associated with it, while calculating the heat loads for liquid recycle and net fresh feed.
(3) Split in benzene column is perfect with 100% recovery of benzene in distillate and 100% recovery of toluene and diphenyl in bottoms. Amount of hydrogen and methane exiting from stabilizer column is negligible.

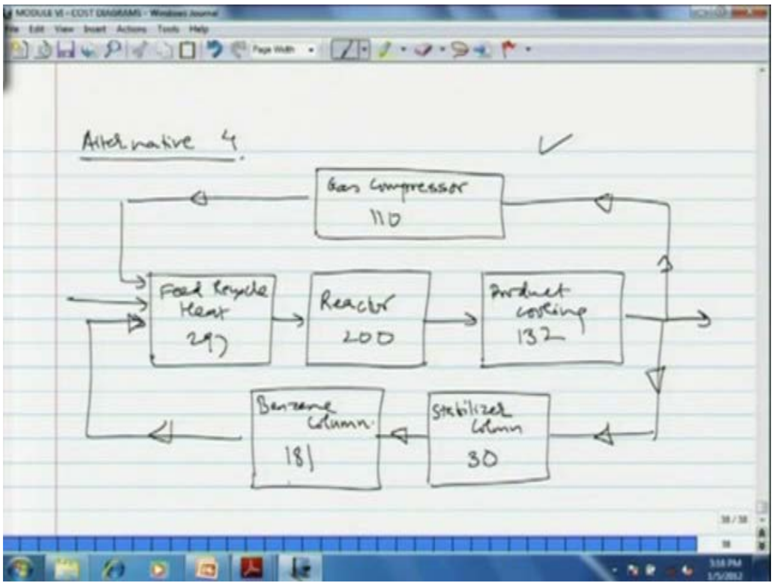
Table 1: Film transfer coefficients of various streams

Heat Exchanger	Stream 1 coefficient, h ($kW/m^2 K$)	Stream 2 coefficient, h ($kW/m^2 K$)
FEHE 1	0.69 (Reactor feed)	0.69 (Reactor effluent)
Reboiler of Stabilizer Column	1.57 (Stabilizer bottoms stream)	0.69 (Reactor effluent)
Reboiler of Benzene Column	1.57 (Benzene bottoms stream)	0.69 (Reactor effluent)
FEHE 2	1.57 (Reactor feed)	0.69 (Reactor effluent)

First assumption is that face splits term is perfect which we means that gas living in flash drum a mixture of hydrogen and methane, does not contain any vapor of toluene and benzene of course, this is not the realistic assumption, but for our initial calculation we can make that particular assumption. Because, the quantity of benzene and toluene giving with that particular gas relatively small compared to the production rate or rate of the total feed of toluene.

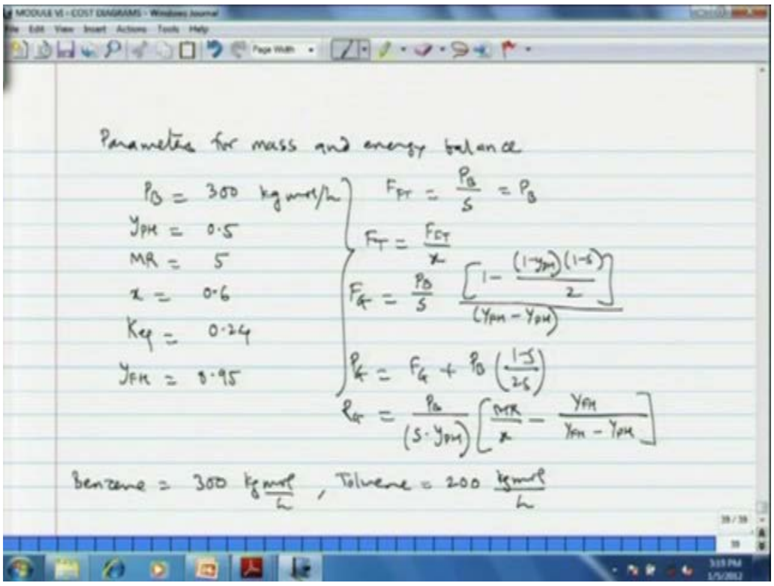
Now, the second assumption is biphenyl in the recycle much smaller than toluene. So, ignore the heat duty associated with it while, calculating the heat loads, and the third assumption is that split in benzene column is perfect with 100 percent recovery of benzene in distilled 100 percent of toluene and biphenyl in bottoms, amount of hydrogen methane existing comes stabilizer column can be taken as negligible. So, with this assumption and with this data, we have to prepare a cost allocation diagram.

(Refer Slide Time: 40:51)



Now, we have already made lumped cost diagram in previous exercise which is right there on your screen. And now, we start with that particular thing let us now, write down all the parameters that are given.

(Refer Slide Time: 41:02)



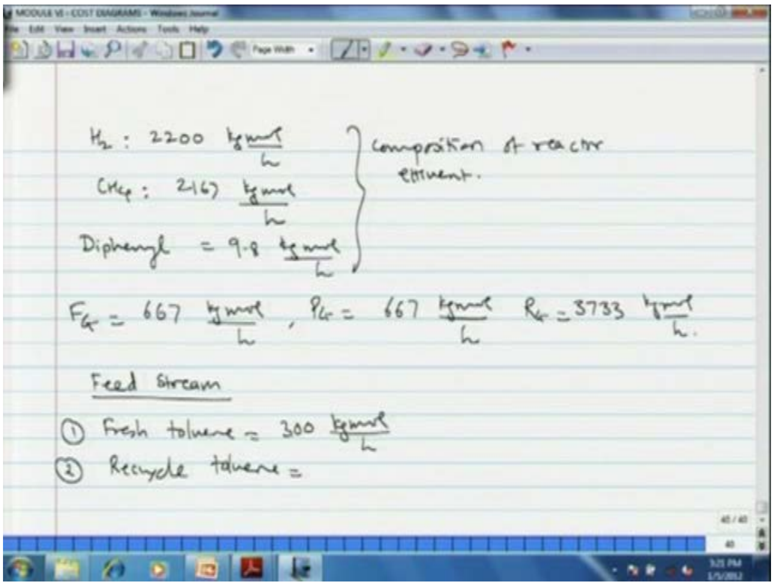
Parameters for mass and energy balance, production data of benzene that we denote by P B 300 kg per mole per hour y P H mole fraction of hydrogen in per jigas 0.5, molar ration of hydrogen to aromatics reactor inlet 5 per pass conversion that we denote by x is

0.6, then equilibrium constant K e q is 0.24 in reactor temperature and y F H the mole fraction of hydrogen in fresh gas or makeup gas is 0.95.

Now, with this parameters I am going to give you the mass balance directly, but you can very easily calculate it I will list I will give for you convince formulae F F T the Feed data Fresh Toluene is P B by S. Since, S is 1 it is equal to P B then total feed rate of toluene F T is F F T by x, then fresh gas is P B by S into 1 minus 1 minus y P H into 1 minus S by 2 divided by y F H minus y P H all of this formulae we have derived in module 2.

So, you are suppose to go back to module 2 and revise to see how this formula have come per jigas is fresh gas plus P B into 1 minus 2 S R G recycle gas is equal to P B divided by S into y P H into M R by x minus Y F H divided by Y F H minus Y P H. Now, this formula we have already derived we are simply going to put this numbers into this formula and then obtain the following values. Benzene we are given 300 kg mole per hour then toluene 200 kg per hour.

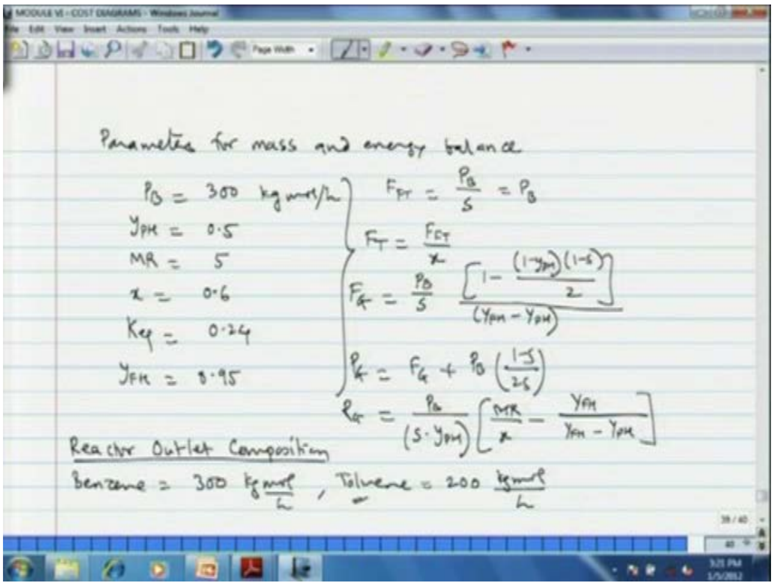
(Refer Slide Time: 44:10)



Then hydrogen 2200 kg mole per hour, methane 2167 kg mole per hour and diphnial is 9.8 kg mole per hour. This is the composition of reactor effluent, the fresh gas F G is 667 kg per mole hour, for each gas P G is also 667 kg mole per hour and recycle gas R G is 3733 kg mole per hour.

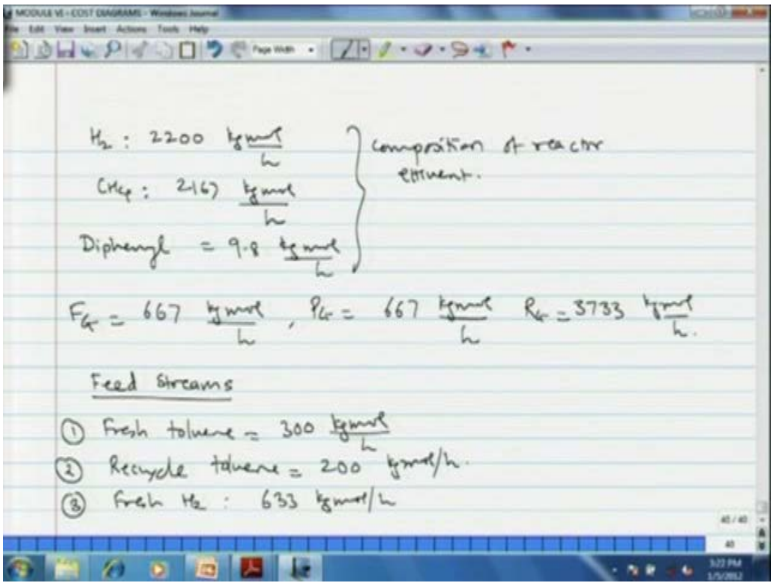
Now, if we split the reactor effluent into recycle purge and then calculate the feed steam composition. Then we get following values feed stream fresh toluene will be equal to 300 kg mole per hour because that is production rate of benzene, then recycle toluene we assume complete recovery and recycle. So, all of the un reacted toluene that is there as we listed in previous is this thing toluene on the reacted toluene.

(Refer Slide Time: 46:07)



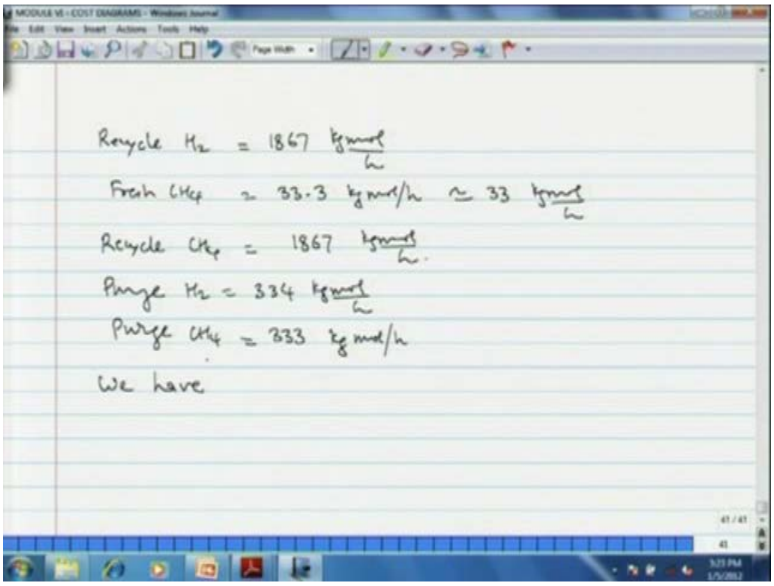
This is reactor outlet composition what we have listed before.

(Refer Slide Time: 46:23)



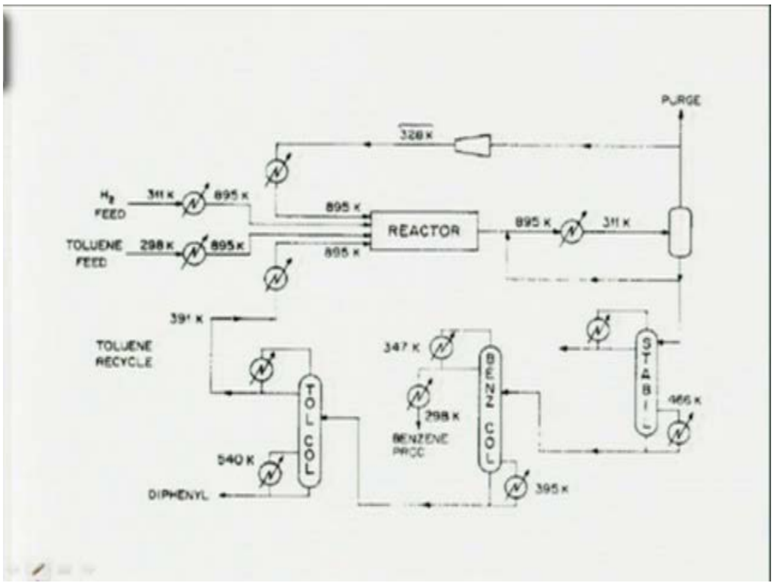
Now we are writing the reactor inlet composition or the feed streams recycle toluene 200 kg per hour. Then fresh hydrogen that will be 0.95 times the fresh gas 633 kg mole per hour.

(Refer Slide Time: 46:47)



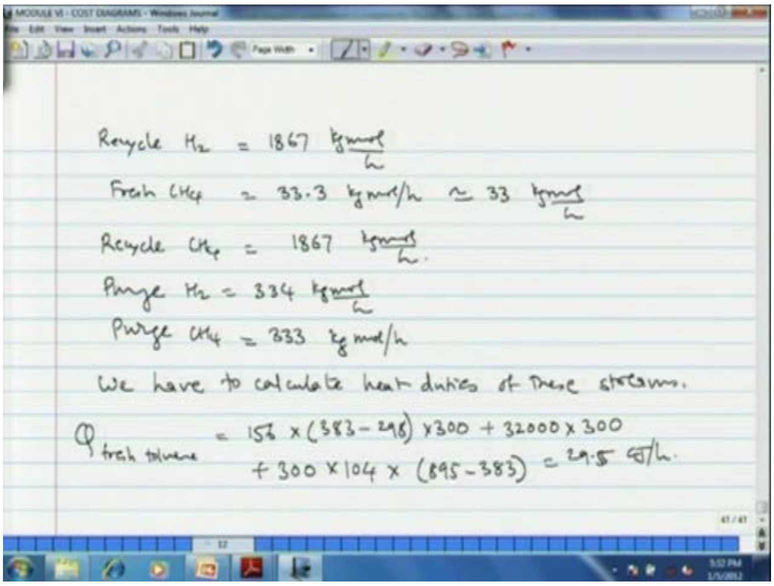
Then recycle hydrogen, that will be 50 percent of the recycle gas 0.5 to recycle gas that is 1867 kg mole per hour. Then fresh methane like methane that enters the impurity with the fresh gas that is fresh methane that is equal to 5 percent of the gas 33.3 kg mole per hour or you can take only 33 for simplification and recycle methane is 50 percent of recycle gas that is again 1867 kg mole per hour. The purge gas total is 667, so purge hydrogen is 334 kg mole per hour and purge methane is 333 kg mole per hour. And now, we have to calculate the heat duty of each of these streams, having done the material balance we have to do the energy balance for flow sheet. Now, to do the energy balance we have to look at the various temperature that are involved in flow sheet.

(Refer Slide Time: 48:11)



Here you can see that the fresh gas is heated from 311 Calvin to at 95 Calvin, the recycle gas heated from 328 Calvin to 895 Calvin, the recycle toluene and biphenyl is heated from 391 Calvin to 895 Calvin and fresh toluene heated from 298 Calvin to 895 Calvin. Now, if we have to calculate activity on all the components, like fresh hydrogen recycle hydrogen, fresh methane recycle methane fresh toluene and recycle toluene and benzene, so on and so forth. Then we have to take into consideration the sensible heat plus the heat of exchange in case of toluene and benzene and then the super heating of the vapor. Now, we shall see the heat duty of each of the stream.

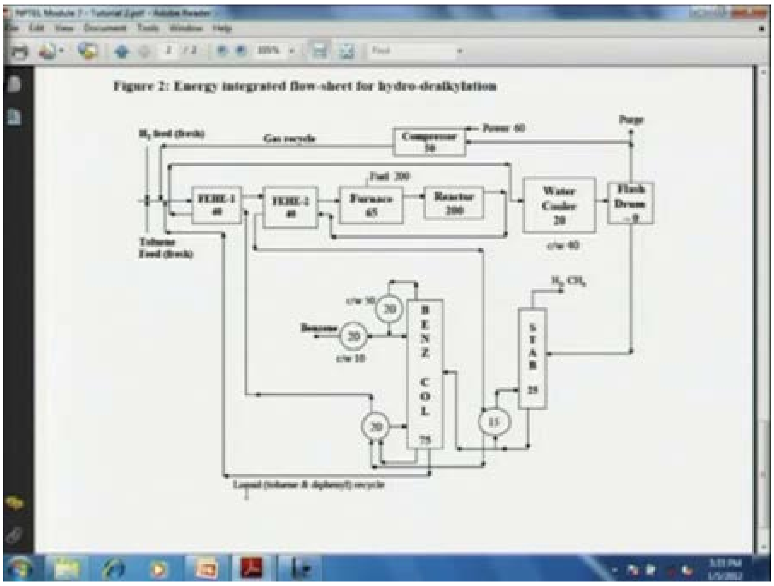
(Refer Slide Time: 49:15)



Now, let us say the heat duty of fresh toluene, heat duty we denote by letter Q fresh toluene, the liquid toluene has heat capacity of 156 joule pre mole per Calvin it is heated from 298 to it is boiling point, which is 110 degree centigrade or 383 Calvin. So, this is the sensible heat 300 kg mole is the feed plus the heat require for the face exchange that is 32,000 joule per mole or joule kilo per mole is the latent heat into 300 kilo mole per hour plus the separating of the 300 kilo moles of vapor the heat capacity of the kilo mole is 104 and the super heating from the boiling 0.383 to 895 Calvin.

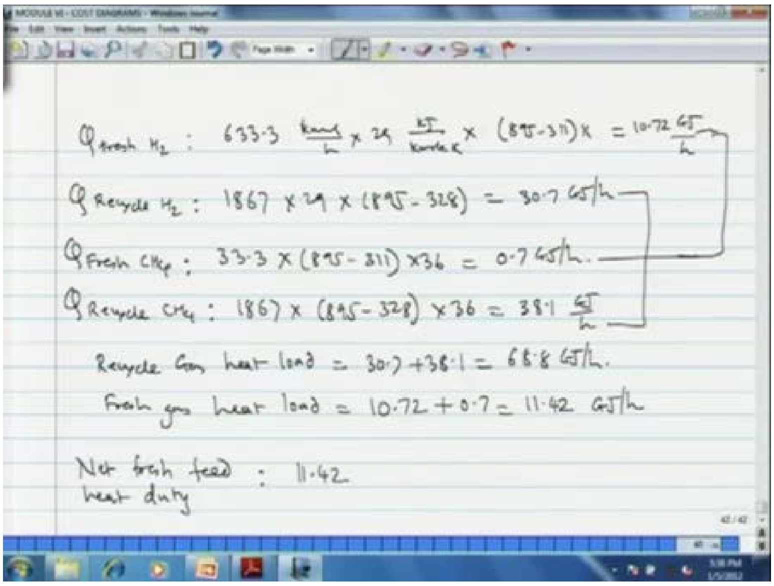
So, this the total heat that is absorbed or that is require for heating fresh toluene, that turns out to be 29.55 giga joule per hour. And similarly, we can calculate the heat duty on other streams; you must note that for recycle toluene the temperature is 395 Calvin, which is higher than the boiling point of the pure toluene, which is 383 Calvin, and this due to presence of biphenyl in the recycle stream. If you see the flow sheet that was there you have the flow sheet indicate recycle of biphenyl.

(Refer Slide Time: 50:58)



Here and therefore, the temperature of recycle toluene is slightly higher, than the boiling point of toluene. So, but those minor things we are going to ignore in our calculation.

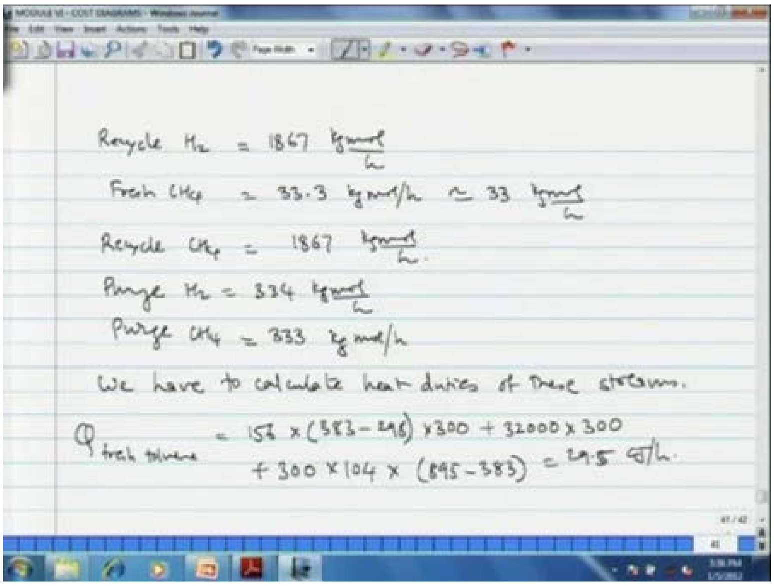
(Refer Slide Time: 51:22)



Now, the heat duty on fresh hydrogen. Q fresh hydrogen, the total moles of fresh hydrogen are 633.3 kilo mole per hour into the latent heat 29 kilo joule per kilo mole per Calvin into the temperature that is the fresh hydrogen is heated from 311 Calvin to 895 Calvin. So, this together comes out to be 10.7 giga joule per hour. And now, I will give the other heat duties you can calculate your self it is pretty straight forward recycle hydrogen 1867 kilo mole per hour 29 the heat capacity and same temperatures 395, but from 328 Calvin.

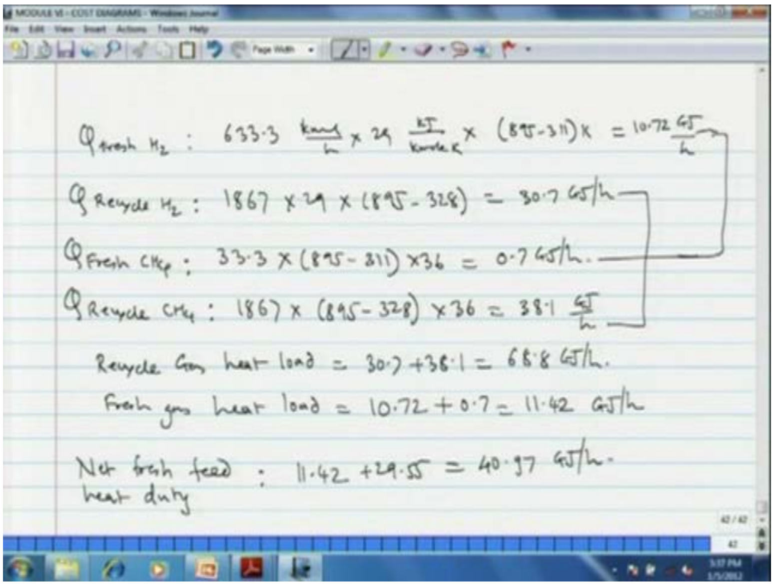
This turns out to be 30.7 giga joule per hour, then the heat duty for fresh methane 33.3 kilo mole per hour into the temperature 895 minus 311 into 36 the heat capacity 0.7 giga mole per hour. Then Q for recycle methane 1867 molar flow rate temperature 895 minus 328 into 36 38.1 giga joule per hour. Now, if you see the recycle heat load, recycle gas heat load you have to sum up the heat load on hydrogen and methane. Recycle hydrogen like this heat load 30.7 plus 38.1 that turns out to be 68.8 giga joule per hour. Then fresh gas load fresh, that will be 10.72 basically, this one 10.72 plus 0.7, so 11.42 giga joule kilo per hour. Now, when we say net fresh feed heat duty, we have to add up heat duty fresh toluene, fresh hydrogen and fresh methane. Now, fresh toluene oh sorry fresh hydrogen plus fresh methane we just calculated 11.42 plus fresh.

(Refer Slide Time: 54:58)



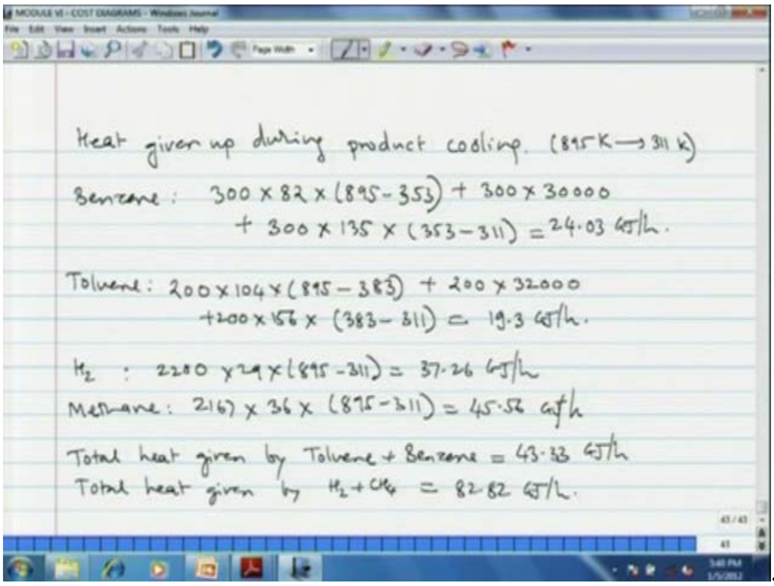
Toluene we calculated as 29.55 that we add here.

(Refer Slide Time: 55:03)



This turn out to be 40.97 giga joule per hour. So, that is the net fresh heat duty.

(Refer Slide Time: 55:24)

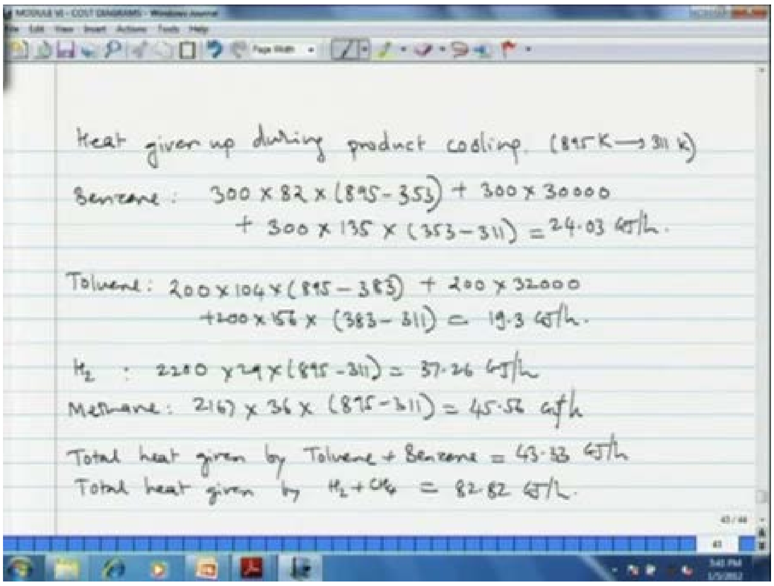


Now, we have to calculate the heat given up during product cooling from 895 Calvin to 311 Calvin. So, this temperature is same for all, first product benzene the total production rate is 300 the vapor heat capacity 82 from 895 gets cooled to it is saturation temperature 80 degree centigrade or 353 Calvin plus 300 into 30,000 that is the heat associated with face change heat liberated during face change plus the sub cooling of the exchange 300 into 135 that is liquid face heat capacity of benzene into 353 minus 311 that turn out to be 24.03 giga joule per hour.

Similarly, for toluene 200 mole toluene remain un reacted the vapor face heat capacity 104 from 895 to it is saturation temperature 383 plus the face change latent heat 200 into 32,000 plus 200 into 156 latent heat in liquid face from saturation temperature to 311 Calvin this comes out to be 19.3 giga joule per hour. And then for hydrogen 2200 is the exit flow rate into 29 heat capacity into 895 minus 311 this is to 37.26 giga joule per hour and for methane.

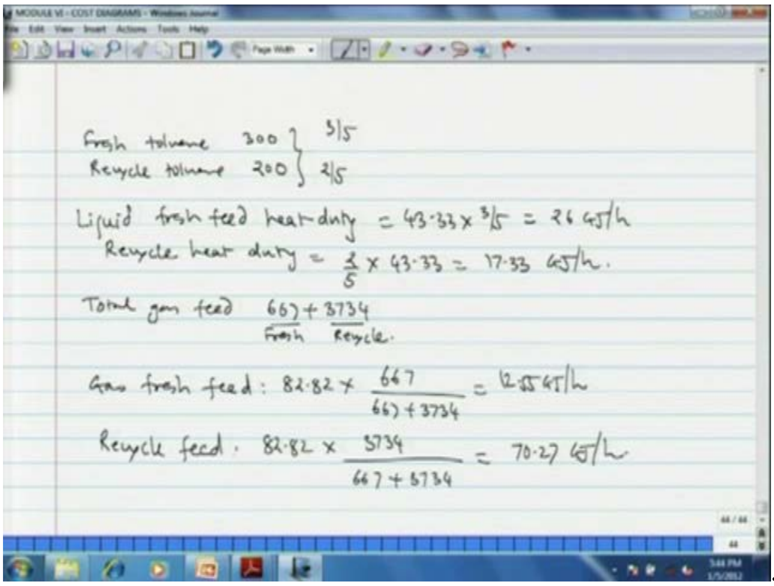
It is 2167 into 36 into 895 minus 311 that is 45.56 giga joule per hour. Now, the total heat given up by condensable components like toluene plus benzene which ultimately end up in liquid face is 43.33 giga joule per hour and total heat given by hydrogen plus methane gives 82.82 giga joule per hour. Now, the heat given up during product cooling as to be distributed between fresh feed and recycle feed that is liquid as well as gas feed in the proportion of molar flows product forms from the feed streams this is the strategy we adopted while preparing the cost allocation diagram. In the previous lecture we had the toluene feed fresh feed to recycle in the ratio 3 as to 1. So, we split all the cost of the column in the ratio 3 as to 1, here it is different. So, we have to first allocate the heat duty in the proportion of molar flow rates and there after distribute the cost.

(Refer Slide Time: 59:35)



We have total heat given up by liquid streams 43.33.

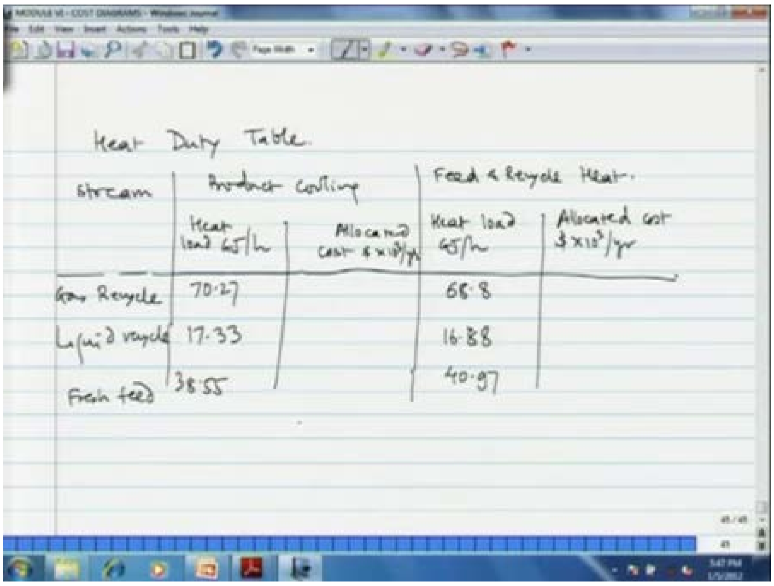
(Refer Slide Time: 59:42)



Now fresh toluene is 300 recycle toluene is 200 therefore, we have to distribute the heat duty in the proportion 3 as to 5 and 2 has to 5 for the net fresh feed and the recycle feed. So, that we do now, liquid fresh feed heat duty like the component of product cooling heat duty associates with liquid fresh feed is 43.33 into 3 by 5 that is 26 giga joule per hour than recycle heat duty or the fractions of product cooling heat duty allocate to recycle stream is 2 by 5 into 43 by 3, that is 17.33 giga joule per hour.

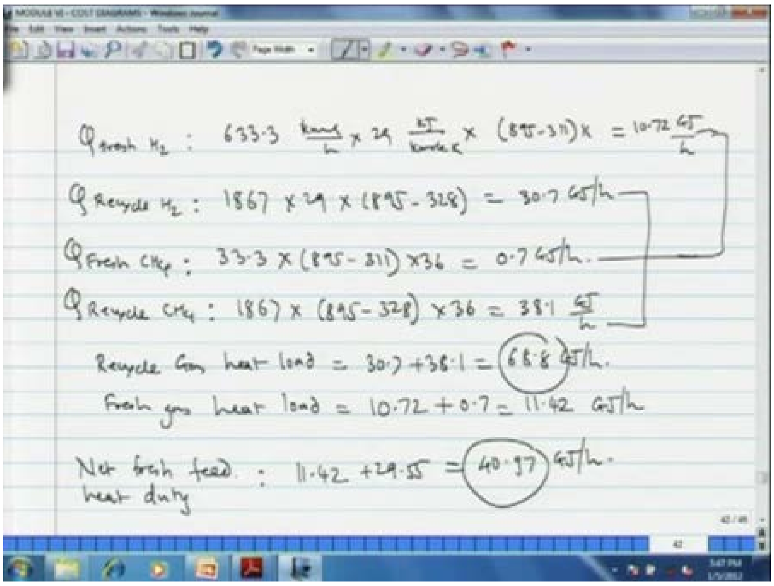
Similarly, the total gas feed is 667 of the fresh gas plus 3734 of recycle gas. And therefore, the heat duty on cooling of the gas component, gas product component will be allocate to fresh stream and recycle stream in this proportions the total heat duty as we calculated was 82.82 giga joule per hour that we are going to distribute now, 12.55 giga joule per hour for the fresh feed and recycle feed 70.27 giga joule per hour. And now, with this we can prepare heat duty table.

(Refer Slide Time: 1:02:23)



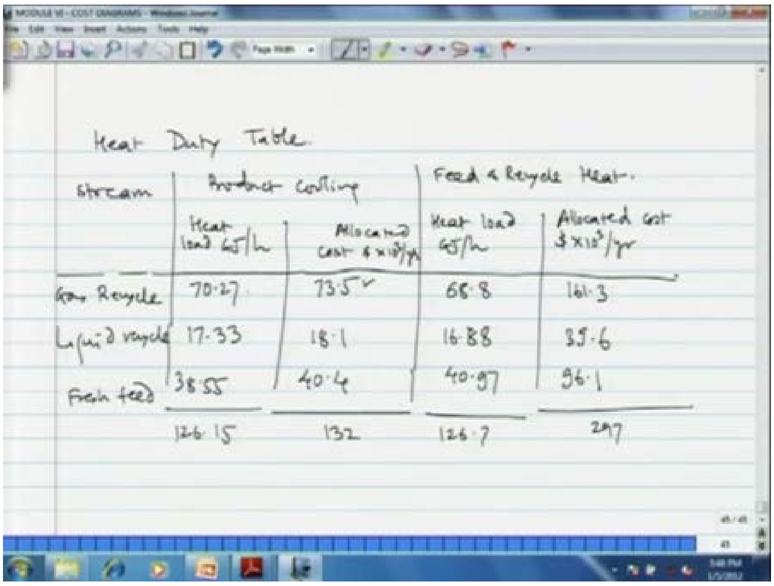
Stream, operation, heat load giga joule per hour and allocated cost the 3 streams cost elements as we called them are gas recycle, liquid recycle and fresh feed and we just distributed the heat duties the total gas heat recycle of component of product cooling heat duty was 70.27 we just calculated here 70.27 this 1. So, that we list here liquid recycle was 17.33 and fresh feed was 38.55. Similarly, the fresh reactor feed heating the gas recycle heating as we calculated here.

(Refer Slide Time: 1:04:50)



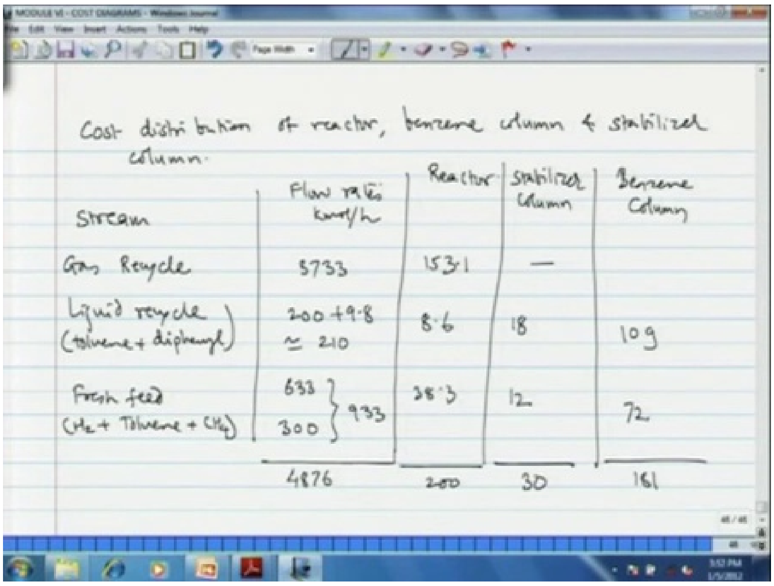
Was 68.8 than fresh gas for net fresh heating was 40.97 and then liquid recycle was 16.88.

(Refer Slide Time: 1:05:32)



The total cost of product cooling as we found in cost allocation diagram was 132000 dollars the total cost reactor cost feed heating as we found in cost allocation diagram was around 297000 dollars. Now, distribute these in total quantity proportion of the heat loads. Total heat load of product cooling is 126.15 giga joule per hour the total heat load on heat power is 126.7 giga joule per hour, and then we distribute accordingly the cost. It is just 70.27 divided by 126.15 into 132 is 73.5 like that. Similarly, here 68.8 divided by 126.7 into 297 is 161.3 and similarly, the other cost 96.5. Now, having done this we can now, make a cost allocation diagram after we distribute the cost of reactors and stabilizer and benzene column as per the molar flow rates.

(Refer Slide Time: 1:07:08)

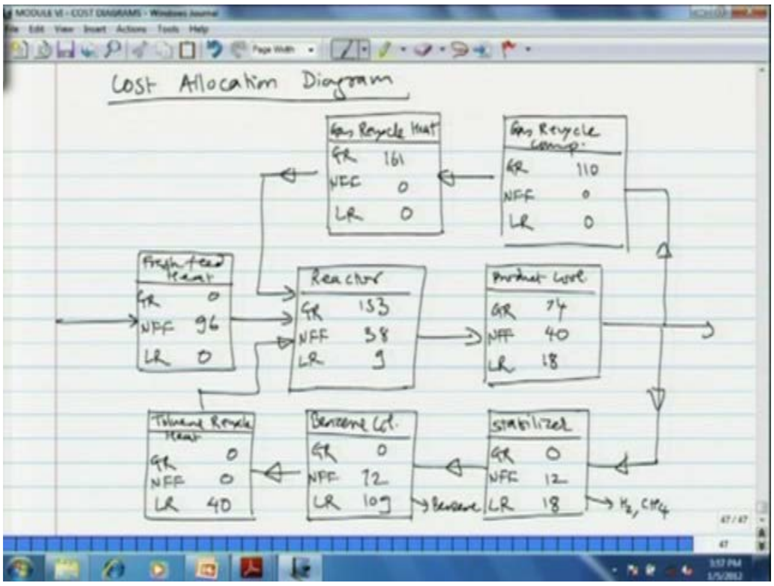


So, the cost distribution of reactor, benzene column and stabilizer column. Stream gas recycle, liquid recycle that is toluene plus biphenyl and fresh feed, this hydrogen plus toluene plus methanol of course, of a flow rates we have already calculated you have to only summed them up, gas recycle kilo mole per hour 37 gas recycle 3733 kilo mole per hour. Now, liquid recycle was 200 toluene you can a calculate with the k equivalent that is given the equilibrium quantity of biphenyl that is present which state forwards you have done in previous exercisers.

So, I am not going to tell here, I it is left as a exercise, but I give the final answer, that is the equilibrium quantity of biphenyl in the present situation will be 9.8 kilo mole per hour. So, 200 plus 9.8 that approximately tick as 210 moles than fresh hydrogen 633.3 or just 633 you can take and the toluene the fresh toluene 300 moles 933. And then we distribute the cost of reactor, stabilizer and benzene column as per this reactor the total cost was 200,000 dollars distributed in proportion the total molecular by the way is 4876.3 you can approximately take 4876.

And then distribute the cost 153 8.6 38.3 or 153.1 to be get exact. Then the stabilizer column, there is no recycle gas recycles in the stabilizer. So, that is 0 and then the total 30,000 dollars are distributed in proportion 18 as to 12 to liquid recycle and fresh feed than benzene column, the total cost was 181000 dollars distributed as 109 and 72 other dollars in proportion of liquid recycle fresh feed. Now, having done this we can, now prepare the cost allocation diagram.

(Refer Slide Time: 1:10:46)



Cost components are, reactor cost elements every where, cost elementary gas recycle net fresh feed liquid recycle. I am showing now, the products that comes out of stabilizer H 2 plus H 4 and the product of benzene column benzene. Now, we pick up all the numbers that are given in previous pages well, for reactor 153 38 9 for product cooling 74 40 18 these are adjusted to nearest integer in some cases gas recycle compression 110 0 0 gas recycle heating 161.3 0 0 or you can take just 161.

Than net fresh feed heating gas recycle 0 net fresh feed 96 liquid recycle 0 toluene recycle heating gas recycle component 0 N F F 0 L R the liquid recycle 39.6 or you can take as 40 approximately benzene column gas recycle 0 net fresh feed 72 liquid recycle 109 stabilizer gas recycle 0 net fresh feed 12, and liquid recycle 18. And this completes the cost allocation diagram. However we have not shown in this cost allocation diagram that losses that our in the system.

For example, what are the losses well the first loss is that the loss of benzene in the purge stream we have assume the perfect stream in flash term. So, there is the loss of benzene and toluene to benzene and purge, so there is always some loss. Than the porch gas itself loss that loss we can estimate the total hydrogen in the purge is 333.3. So, if you multiply by that by 8000 hours per year and a cost of hydrogen per kg converting multiplying by 2 further of the molecular weight you can estimate the exact loss of hydrogen and toluene and benzene.

For toluene and benzene you will have to do the flash calculations which are available in any standards texts like mass transfer operation bulk flash calculation will also be covered in the mass transfer operations course. So, this is how we prepare cost allocation diagram. And now this completes our tutorial as well as module on cost diagram side and big screening of processes alternative.