

# Energy Conversion Technologies (Biomass and Coal)

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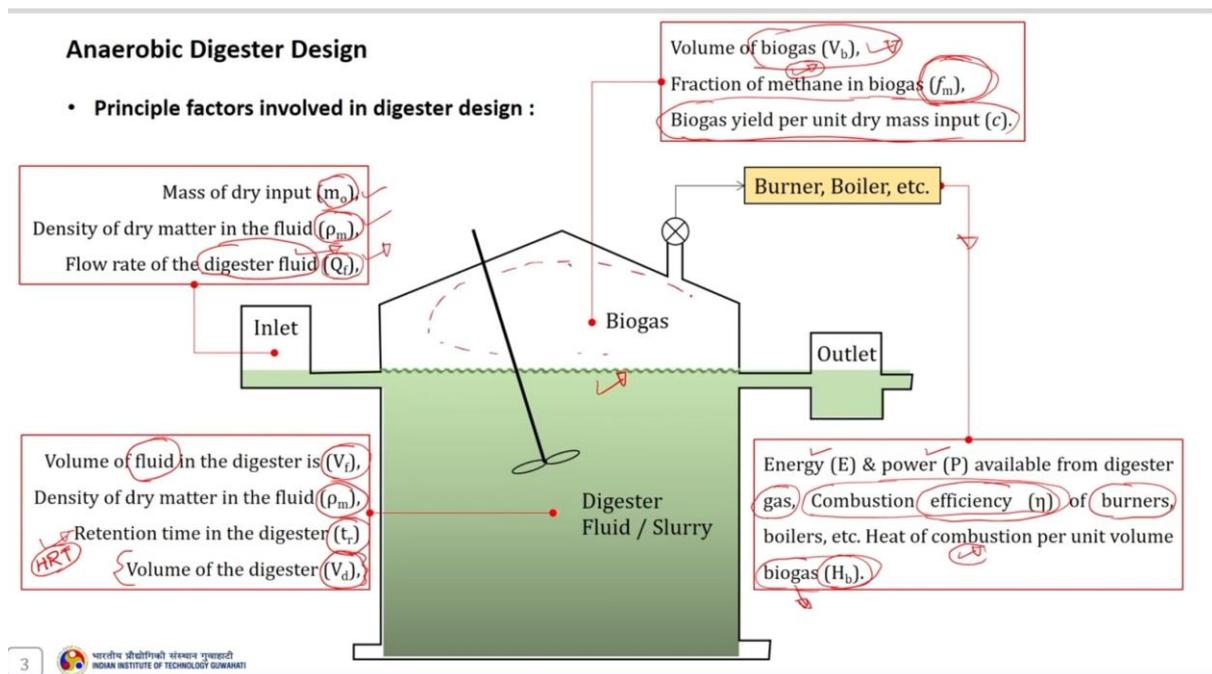
## Lecture 23

### Practice examples (Biogas and Bio-ethanol production)

Good morning everyone.

Welcome to this third lecture of module 5. If you recollect our discussion in the previous two lectures, we discussed about two different biochemical conversion processes that is anaerobic digestion and alcoholic fermentation. So, in this lecture, we will practice few examples on the concept covered in this module. Before that, we will discuss one or two important topics that is principal factors involved in digester designing and that is related to the anaerobic digestion process and theoretical ethanol yield that is related to the alcoholic fermentation process. Because the digester sizing involves certain parameters or factors that need to be taken into consideration while sizing the digester that means while designing the digester. So, let us discuss about these principal factors or I would say the principal parameters that are important in sizing the digester.

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So, if you look at this particular slide here, so, this schematic here it represent the digester which is used for the anaerobic digestion process. In that the input parameter that is mass of dry input represented as  $M$  suffix  $O$ , then density of dry matter in the fluid that is represented as  $\rho$  and flow rate of digester fluid which is represented as  $Q$  suffix  $F$ . So, in that this flow rate of digester fluid is one of the important factor that need to be taken into consideration while sizing this digester.

Next is the digester fluid or digester slurry. So, in this case the volume of fluid in the digester that is  $V$  suffix  $F$  need to be estimated. Apart from that the density of dry matter in the fluid as just mentioned before that is also important followed by the retention time in the digester and it is represented as  $T$  suffix  $R$ . And if you recollect our discussion in the previous lecture we discuss about this factor and we mention it as HRT that is hydraulic retention time. And this particular factor is very crucial factor in the designing of the digester and the volume of the digester that is  $V$  suffix  $D$ .

So, once we know this information then we can estimate the volume of the digester which is required for the specific flow rate of the digester fluid. And once these parameters are known, then the gas which is released during this anaerobic digestion process needs to be stored in a digester. And for that reason the volume of the biogas need to be estimated for a specific source of feed material. And once we know the volume of the biogas then the fraction of methane in the biogas need to be estimated. And this can be estimated using a standard analytical technique and also the biogas yield per unit dry mass input that is represented as  $C$ .

And the biogas yield is also one of the important and the crucial factor which gives information about the biogas yield from a specific source material which is used for the anaerobic digestion process. And once we know about the gas yield as well as the fraction of methane in the biogas and the volume of the gas which is getting generated in the anaerobic digestion process then comes to the utility of the produced gas. So, once the gas is available from the digester then energy and the power available from the digester gas is also one of the important factor, that is the amount of energy as well as the power which is available in the produced gas. And that depends on the composition of the gas which is getting produced in anaerobic digester followed by the combustion efficiency. If the produced gas is being used for the thermal application then the combustion efficiency of the burners and boilers also plays a role.

Here which is also one of the crucial factor followed by the heat of combustion per unit volume biogas and it is represented as  $H_b$ . So, this is also one of the important factors because if the heat of combustion is calculated per unit volume of the biogas then it would be different than heat of combustion per unit volume of methane. Because after purification process the biogas can be converted into a pure methane form and in that case the heat of combustion per unit volume of the methane need to be considered.

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- The **required gasholder capacity** is an important design parameter for anaerobic digester.
  - If the gasholder capacity is insufficient, part of gas produced will be lost and the remaining volume of the gas will not be enough at the time of demand.
  - If the gasholder is much too large, construction cost will be unnecessarily high.
  - The gasholder must be made large enough to acquire the entire **volume of the biogas** consumed at a time.
- Therefore, **volume of biogas** is an important parameter to design the digester.

Volume of biogas is given by:

$$V_b = c \times m_o \quad (m^3) \quad (1)$$

Volume flow rate of biogas is given by:

$$Q_b = c \times \dot{m}_o \quad (m^3) \quad (2)$$

where,  $c$  ( $m^3/kg$ ) is the biogas yield per unit dry biomass (usually it is 0.2 to 0.4  $m^3/kg$ ),  
 $m_o$  (kg) and  $\dot{m}_o$  (kg/d) are the mass and mass flow rate of dry input.

So, as we discussed before the required gas holder capacity is an important design parameter for the anaerobic digester. That means as we discussed before, this indicates the gas holder capacity. So, this is one of the important parameter in the anaerobic digester. That the capacity of this gas holder need to be estimated properly so that it should be sufficient enough to acquire the entire volume of the gas which is generated during the anaerobic digester process and that is also based on the consumption rate. For example, if the gas holder capacity is insufficient that means suppose this gas holder capacity is relatively smaller then part of the gas produced will be lost. And the remaining volume of the gas will not be enough to match the demand, right. Because, the holder capacity itself is insufficient to acquire the enough volume of the gas, which is getting generated during the anaerobic digester process.

So, as a result some of the gas will be lost and then the remaining volume of the gas will not be sufficient enough to match the demand. Or in case the gas holder is too large then construction cost will be unnecessarily high. Because then the size of the gas holder is sufficiently high. Whereas the volume of the gas which is getting produced is relatively lower than that. And then it incurs the construction cost which is unnecessarily high.

And therefore the gas holder must be made large enough or we can say optimum enough to acquire the entire volume of the gas, which is consumed at a time. So that then the gas which is getting produced at a specific rate can occupy the next cycle of gas in the digester after the gas is getting consumed at a time. Therefore the gas holder must be made large enough to acquire the entire volume of the gas consumed at a time. And because of that the volume of the biogas is an important parameter to design the digester. So, here the volume of the biogas can be estimated using this simple equation here V suffix B represent the volume of biogas and these two terms here represent the mass and mass flow rate of dry input.

Whereas this C represent the biogas yield per unit dry biomass and usually it is in the range of 0.2 to 0.4 meter cube per kg. So, once we know these values then we can estimate the volume of the biogas as well as the volume flow rate of the biogas that is represented as Q suffix B. And if you remember in the previous slide, this particular term, it represent the input parameter that is the mass and the mass flow rate to the digester and with the help of that volume of biogas as well as the volume flow rate of the biogas can be estimated.

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Volume of fluid or slurry in the digester is given by:  $V_f = m_o / \rho_m$  (m<sup>3</sup>) (3)

Volume flow rate of fluid or slurry in the digester is given by:  $Q_f = \dot{m}_o / \rho_m$  (m<sup>3</sup>) (4)

where,  $\rho_m$  (kg/m<sup>3</sup>) is the density of dry matter in the fluid or slurry (usually ~50 kg/m<sup>3</sup>).

$Q_f$  (m<sup>3</sup>/d) is the volume flow rate of the digester fluid.

Volume of the digester is given by:  $V_d = Q_f \times t_r$  (m<sup>3</sup>) (5)

where,  $t_r$  (d) is the retention time in the digester (usually ~8 to 20 days).

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Similarly volume of the fluid or slurry in the digester it is represented as V suffix F, which is equal to M suffix O divided by its density. So, once you know these two term then you can calculate the volume of slurry in the digester followed by that you can also estimate the volume flow rate of the fluid or slurry in the digester which is Q suffix F, equal to the term here if you remember, that is mass flow rate of dry input divided by the density of dry matter in the fluid. So, once we know these two terms, then we can calculate the volume flow rate of the fluid in the digester. And here this term it represents the density of dry matter in the fluid or slurry and it is usually 50 kg per meter cube. So, please note that this is density of dry matter in the fluid and this is not the density of slurry.

And this Q suffix F here, it represent the volume flow rate of the digester fluid. And once we know this volume flow rate of the digester fluid, then we can estimate the volume of the digester. For that we need to know this term here that is T suffix R. And it is the retention time of the material in the digester. And it is usually 8 to 20 days.

Once we know this value the retention time value and QF, then we can calculate the volume of digester and that will be in the meter cube.

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**Energy available from a biogas digester (E)** can be calculated as:

$$E = \eta \times H_b \times V_b \quad (\text{MJ}) \quad (6)$$

**Thermal power available from a biogas digester (P)** can be calculated as:

$$P = \eta \times H_b \times Q_b \quad (\text{MJ/day}) \quad (7)$$

where,  $\eta$  is the combustion efficiency of burners, boilers, etc. (usually ~60%).

$H_b$  (MJ/m<sup>3</sup>) is the heat of combustion per unit volume biogas (approx. 20 MJ/m<sup>3</sup> at 0.01 atm),

$V_b$  (m<sup>3</sup>) is the volume of biogas,

$Q_b$  (m<sup>3</sup>/day) is the volume flow rate of biogas.

Note: CO<sub>2</sub> present in the biogas absorbs some of the heat of combustion of the methane, so overall energy efficiency decreases.

6  INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI Courtesy: Twidell, Renewable Energy Resources, Ed 3, Taylor & Francis, 2015.

Now, once we know the volume of the digester as well as the volume of the biogas, which is generated in the digester, then with the help of that we can calculate the energy available from the biogas, which is getting produced in a digester. And it can be estimated using this equation, which is  $E$  equal to this is the efficiency  $\eta$  suffix  $B$  into  $V$  suffix  $B$  here. And  $V$  suffix  $B$  here is nothing but the volume of biogas and  $H$  suffix  $B$  represent the heat of combustion per unit volume of biogas and it is approximately 20 mega joule per meter cube. Please take a note of this; this is the heat of combustion per unit volume of biogas and not the methane.

And this term here it represents the combustion efficiency of a burner or boiler and it is usually in the range of 50 to 60 percent. Similarly, we can also estimate the thermal power available from a biogas which is produced in a given digester. And it can be calculated using this equation,  $P$  equal to again the combustion efficiency into the heat of combustion per unit volume of the biogas into  $Q_B$ .  $Q_B$  in the sense here is the equation is volume of flow rate of biogas. And then once we know this term we can calculate the power available from a biogas and that will be in the mega joule per day. Now suppose if  $CO_2$  is present in the biogas then it absorbs some of the heat of combustion of the methane so the overall energy efficiency decreases accordingly.

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Alternatively, the energy available from a digester ( $E$ ) can be determined from the biogas composition:

$$E = \eta \times H_m \times f_m \times V_b \quad (8)$$

where,  $H_m$  is the heat of combustion of methane (56 MJ/kg, 28 MJ/m<sup>3</sup> at STP)  
 $f_m$  is the fraction of methane in the biogas.

The biogas obtained directly from the digester, contains  $f_m$  between 0.5 and 0.7.  
 However,  $f_m$  can be increased to nearly 1, by passing the gas through a water or solvent to absorb the  $CO_2$ .

7  COURTESY: TWIDELL, Renewable Energy Resources, Ed 3, Taylor & Francis, 2013.

Therefore, alternatively the energy available from digester gas can also be determined from the biogas composition. But for that purpose we need to estimate the composition of the biogas first. And if we know that the composition of the biogas includes 60 percent methane and 30 or 35 percent CO<sub>2</sub> and remaining traces of other gases, then based on that, considering the fraction of methane in the biogas we can also alternatively, calculate the energy available from a digester gas. But here it will be based on the methane percentage in the gas composition and that is termed as a fraction of methane in the biogas and here then equation would be in the form of combustion efficiency into H suffix M.

And here H suffix M represents the heat of combustion of methane. And that is close to 28 MJ per meter cube at standard temperature and pressure. Now if you compare this equation with the previous equation here, so here the energy available from the biogas is estimated using this equation. So this H<sub>b</sub> represents here the heat of combustion per unit volume of biogas, right. Because here it includes the total composition of biogas, which includes methane, CO<sub>2</sub> and traces of other gases.

However, in this equation this H suffix M, it represent the heat of combustion of methane. So for that reason the fraction of methane present in the biogas need to be estimated. And just by multiplying this term here we can easily calculate the net energy which is available from the digester gas but it is from a purified gas that is purely methane. As mentioned earlier also the biogas obtained directly from the digester contains fraction of methane between 0.5 to 0.7. However this methane percentage it can be also increase to nearly 100% by passing gas through a water or solvent to absorb the CO<sub>2</sub>. And the traces of other gases as well so that gas can be cleaned up to produce pure methane as a gas.

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**Example 1.** On an average, a dairy cow produce 35 kg of total wet manure per day having moisture content of 87% (by weight), density of 50 kg/m<sup>3</sup>, and biogas yield of 0.25 m<sup>3</sup>/kg of dry manure. Calculate:

- ✓ (a) Volume of a biogas digester suitable for the output of 700 dairy cows (assume retention time of 18 days);
- ✓ (b) Power available from the digester (assume LHV of biogas as 20 MJ/m<sup>3</sup> and a burner efficiency of 60%).

**Solution:**

Given data:

The retention time in the digester ( $t_r$ ) = 18 days

Burner efficiency ( $\eta$ ) = 60% = 0.6

Heat of combustion of biogas ( $H_b$ ) = 20 MJ/m<sup>3</sup> (i.e. LHV)

Biogas yield ( $c$ ) = 0.25 m<sup>3</sup>/kg of dry manure

Density of dry matter in the fluid or slurry ( $\rho_m$ ) = 50 kg/m<sup>3</sup>.

So now after learning about this sizing of the digester, let us try to solve one example on this concept. That is how to design a digester with the help of the given information. So in this case here we need to calculate the volume of a biogas digester which is suitable for a output of 700 cows in a dairy farm and assume the retention time is around 18 days.

And also we need to estimate the power available from a digester. Here we need to do one small assumption that is the LHV of biogas is considered as 20 MJ per meter cube and the burner efficiency is 60%. And the given data here is like on average dairy cow produces around 35 kg of total weight manure per day. So here the manure is wet manure and this quantity is given on per day basis, having a moisture content of 87% by weight and the density is 50 kg/m<sup>3</sup>.

And the biogas yield is around 0.25 meter cube per kg of dry manure. So with the help of this given information we need to estimate these two terms that is volume of the biogas digester and the power available from a digester gas. So let us try to solve this example. So given data, as we mentioned, the retention time in the digester is given as 18 days, burner efficiency is mentioned as 60% that is 0.6 and heat of combustion of biogas that is H suffix B is 20 mega joule per meter cube and that is low reading value.

Biogas yield that is represented as C is 0.25 meter cube per kg of dry manure and the density of the dry matter in the fluid or slurry that is represented as a term here is 50 kg per meter cube. So I am just repeating again this is the density of dry matter and not the density of slurry.

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$\checkmark$  Dry manure produced = wet manure  $\times$  fraction of dry manure =  $35 \text{ kg/d/cow} \times (1 - 0.87) = 4.55 \text{ kg/d/cow}$

$\checkmark$  Mass flow rate of dry manure input to the digester ( $\dot{m}_o$ ) =  $4.55 \text{ kg/d/cow} \times 700 \text{ cows} = 3,185 \text{ kg/d}$

(a) To calculate the volume of a biogas digester suitable for the output of 700 dairy cows:

$\checkmark$  Volume of the digester is given by:  $V_d = Q_f \times t_r$

The volume flow rate of the digester fluid ( $Q_f$ ) can be calculated from the mass flow rate as:

Volume flow rate of fluid in the digester is given by:  $Q_f = \dot{m}_o / \rho_m = (3,185 \text{ kg/d}) / (50 \text{ kg/m}^3) = 63.7 \text{ m}^3/\text{d}$

The retention time in the digester is given,  $t_r = 18 \text{ days}$

Thus, the volume of the digester :  $V_d = Q_f \times t_r = 63.7 \text{ m}^3/\text{d} \times 18 \text{ d} = 1146.6 \text{ m}^3$ . (Answer)

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So since we know the wet manure which is getting produced on daily basis and the fraction of dry manure is also known, then with the help of these two terms we can calculate the dry manure which is getting produced on a daily basis. So this is the term which is weight manure on daily basis available and the moisture contained in the wet manure is 87%.

So once you remove this moisture contained from the manure so the remaining component is a dry part of the manure. So once you multiply these two terms we will get the value in the form of 4.55 kilogram per day per cow. So this is the dry manure which is getting produced on a daily basis. Similarly the mass flow rate of the dry manure input to the digester that is represented in this form is the dry manure produced into the number of cows in the dairy farm will get the value like 3185 kg per day but that is mass flow rate of the dry manure which is input to the digester.

Now let us calculate first the volume of biogas digester which is suitable for the output of 700 cows in a dairy farm. So as we know the equation of the volume of the digester. It is given as  $V$  suffix  $D$  equal to  $QF$  into retention time and this specific term is given in this example. However we need to calculate this  $Q$  suffix  $F$  that is volume flow rate of the digester fluid and it can be calculated from the mass flow rate. As we have just estimated this value here the mass flow rate and the density of dry matter is given in the example.

So with the help of these two terms we can calculate the volume rate of fluid in the digester that is 3185 kilogram per day divided by the density that is 50 kg per meter cube. So once this gets cancelled, we get the volume flow rate of the fluid as 63.7 meter cube per day and retention time is 18 days. So once we multiply this two term, we get the volume of digester, we get the volume of the digester as 63.7 into 18 days. So once it cancels out the volume comes out to be around 1146.6 meter cube. Because if we look at the volume flow rate of the fluid in the digester the value itself is sufficiently high. So accordingly the volume of the digester also will be significantly high for the specific retention time of 18 days.

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(b) To calculate the thermal power available from the digester:

Power available from a biogas digester is given by:  $P = \eta \times H_b \times Q_b$  (MJ/d)

Volume flow rate of biogas is given by:  $Q_b = c \times \dot{m}_o$  ( $m^3/d$ )

We have, Mass flow rate of dry manure input to the digester ( $\dot{m}_o$ ) = 3,185 kg/d

Biogas yield ( $c$ ) = 0.25  $m^3/kg$  of dry manure

Burner efficiency ( $\eta$ ) = 0.6

Heat of combustion of biogas ( $H_b$ ) = 20 MJ/ $m^3$

Therefore,  $Q_b = c \times \dot{m}_o = 0.25 \text{ m}^3/\text{kg} \times 3,185 \text{ kg/d} = 796.25 \text{ m}^3/\text{d}$

$P = \eta \times H_b \times Q_b = 0.6 \times 20 \text{ MJ/m}^3 \times 796.25 \text{ m}^3/\text{d} = 9555 \text{ MJ/d}$

Power available from a biogas digester =  $9555 \frac{\text{MJ}}{\text{d}} \times \frac{1 \text{ d}}{24 \text{ h}} \times \frac{1 \text{ h}}{60 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ s}} = 0.1106 \frac{\text{MJ}}{\text{s}} = 0.1106 \text{ MW}$  (Answer)

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So now once we know the volume of the digester, now we can estimate the thermal power which is available from the digester gas.

So the power available from a biogas digester it can be estimated using this equation. This is the combustion efficiency heat of combustion of biogas and  $Q$  suffix B is volume rate of biogas. And this volume rate of biogas it can be estimated using this equation here that is C into  $M_0$ . And this volume flow rate of biogas can be estimated using this equation here. Since these values are known then we can estimate this volume flow rate of biogas.

Since we have already estimated this mass flow rate of dry manure input to the digester that is this particular term so it is around 3185 kilogram per day. And the biogas yield is given as 0.25 meter cube per kg of dry manure. And the burner efficiency is 60%, and heat of combustion of biogas is given as 20 mega joule per meter cube. Now once we substitute this value in the above equation we can estimate first the volume flow rate of biogas that is 0.25 into 3185. It comes out to be around 796.25 meter cube per day. And similarly we can also calculate the power available from a biogas digester. This term here represent the efficiency that is 0.6 and the heat of combustion of biogas is 20 mega joule per meter cube into volume flow rate of biogas. So the power available from the biogas digester it is around 9555 mega joule per day and we can convert this value into megawatt by using this simple unit conversion here.

So this is in the mega joule per day so we can convert into 24 hours first followed by minute and then seconds so the value would be around 0.1106 mega joule per second. So mega joule per second is nothing but megawatt so the power available from this design digester will be around 0.1106 megawatt. So I hope now it is clear how to estimate the volume of the digester as well as the thermal power available from the digester.

So now let us move on to the next example.

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**Example 2.** Calculate the volume of a cow manure based biogas plant required for cooking needs of a family of four adults and lighting need with three 100 CP lamps for five hours daily. Also calculate the required number of cows to feed the plant. Assume biogas required for cooking is about  $0.227 \text{ m}^3/\text{person}/\text{day}$ . Gas required for lighting a 100 CP (candle power) mantle lamp is  $0.126 \text{ m}^3/\text{h}$ . (Assume: Retention time in the digester = 18 days, Biogas yield ( $c$ ) =  $0.25 \text{ m}^3/\text{kg}$  of dry manure, Density of dry matter in the fluid or slurry =  $50 \text{ kg}/\text{m}^3$ ).

**Solution:**

Gas required for cooking for the family of four adults =  $4 \times 0.227 = 0.908 \text{ m}^3/\text{day}$

Gas required for lighting =  $0.126 \times 3 \times 5 = 1.890 \text{ m}^3/\text{day}$

Total daily gas requirement of the family =  $0.908 + 1.890 = 2.798 \text{ m}^3/\text{day}$

Therefore, Volume flow rate of biogas:  $Q_b = 2.798 \text{ m}^3/\text{day}$

Biogas yield ( $c$ ) =  $0.25 \text{ m}^3/\text{kg}$  of dry manure (given)

Mass flow rate of dry input,  $\dot{m}_o = Q_b/c = 2.798/0.25 = 11.192 \text{ kg}/\text{day}$

$$(Q_b = c \times \dot{m}_o)$$

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So in this example it has been asked to estimate the volume of a cow manure based biogas plant, which is required for cooking needs of a family of 4 adults and lighting need with 300 Cp lamps for 5 hours daily. Also need to estimate the required number of cows to feed this particular plant on daily basis. And assume the biogas, which is required for cooking is about 0.227 meter cube per person per day, and the gas required for lighting a 100 Cp candle power lamp is 0.126 meter cube per hour. So here we have to make certain assumption that is retention time of slurry in the digester is 18 days, Biogas yield 0.25 meter cube per kg of dry manure or dry matter, and density of dry matter in the fluid or slurry is 50 kg per meter cube. So with this given information, let us try to calculate this volume of a plant, which is required for the cooking needs and the lighting needs of a family.

Since we know the gas which is required for a cooking for the family of 4 adults it is around 0.227 meter cube per person per day. So since the family consists of 4 adults so once we multiply 4 into this value we get the value in the form of 0.908 meter cube per day. So this is the amount of the gas which is required on daily basis for the cooking needs. And the gas required for lighting purpose is 0.126 into 3 lamps for 5 hours a day. And which comes out to be around 1.890 meter cube of gas required on daily basis to meet the lighting needs. So the total daily gas requirement is we can just sum up these 2 values and this is the total daily gas requirement of the family. Therefore the volume flow rate of biogas that is  $Q$  suffix B is

around 2.798 meter cube per day. And the biogas yield is given as 0.25 meter cube per kg of dry matter and this value is given.

So based on these 2 values we can easily calculate the mass flow rate of dry input. That is we can simply divide this by this term here and we get the mass flow rate of dry input, and that comes out to be around 11.192 kilogram per day. And this is the equation if you remember; we have used this equation here to calculate this mass flow rate.

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Volume flow rate of fluid in the digester is given by:  $Q_f = \dot{m}_o / \rho_m$

For,  $\rho_m = 50 \text{ kg/m}^3$  (given),  $Q_f = (11.192 \text{ kg/day}) / (50 \text{ kg/m}^3) = 0.2238 \text{ m}^3/\text{day}$

Volume of the digester is given by:  $V_d = Q_f \times t_r$

For,  $t_r = 28 \text{ day}$ ,  $V_d = 0.2238 \text{ m}^3/\text{day} \times 28 \text{ day} = 6.2664 \text{ m}^3$

Therefore, the volume of a cow dung based biogas plant is  $6.2664 \text{ m}^3$ . (Answer)

To calculate the required number of cows to feed the plant:

Mass of dry manure input,  $\dot{m}_o = Q_b/c = 2.798/0.25 = 11.192 \text{ kg/day}$

One cow produce = 4.55 kg dry manure/day

Total cows required =  $11.192/4.55 = 2.45 \approx 3$  cows (Answer)

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Similarly, the volume flow rate of the fluid in the digester can be estimated because the density of the dry matter is also given and this value we have just estimated. So ratio of these 2 will be the volume flow rate of the fluid in the digester. And once we know the volume flow rate of the fluid in the digester as well as the retention time of the fluid in the digester, then we can easily calculate the volume of the digester. So this equation if you remember it is used to calculate the volume of the digester. In this equation this  $Q_f$  value is known as well as the retention time is known.

So by multiplying these 2 values we can estimate the volume of digester and it comes out to be around 6.2664 meter cube. So the volume of this cow manure based biogas plant is this

much. Now once we estimate the volume of digester, now we can estimate the number of cows, which are required to feed this particular digester plant on daily basis.

So the mass of dry manure input it is known that is 11.192 kilogram per day. So since this value is obtained from the given table, in one of the lecture, so with the help of this value we can calculate the total cows. Which are required here, we can just take the ratio of these 2 term here and the value comes out to be around 2.45 which is equivalent to 3. So these many number of cows required to feed the manure in the plant on daily basis.

After learning about the principal factors which affect the sizing of the digester, let us move on to the next important topic that is theoretical ethanol yield in alcoholic fermentation process.

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**Theoretical ethanol yield**

The fermentation reactions of C5/C6 sugars are represented by following equations:

$$3C_5H_{10}O_5 \text{ (Pentose)} \xrightarrow{28-32^\circ\text{C}; \text{Yeast/Enzymes}} 5C_2H_5OH \text{ (Ethanol)} + 5CO_2$$

$$C_6H_{12}O_6 \text{ (Hexose)} \xrightarrow{28-32^\circ\text{C}; \text{Yeast}} 2C_2H_5OH \text{ (Ethanol)} + 2CO_2$$

Compound	Molar mass
$C_{12}H_{22}O_{11}$	342.30 g/mol
$C_5H_{10}O_5$	150.13 g/mol
$C_6H_{12}O_6$	180.15 g/mol
$C_2H_5OH$	46.08 g/mol
$CO_2$	44.01 g/mol
$H_2O$	18.015 g/mol

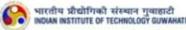
From the mole and mass balance for the fermentation of the hexose sugar (C6):

**180.15** kg of hexose sugar produce **92.16** kg of ethanol & **88.02** kg carbon dioxide.

Thus, **Theoretical ethanol yield (TEY)** for pure hexose sugar =  $\frac{92.16 \text{ kg}_{\text{EtOH}}}{180.15 \text{ kg}_S} = 0.51 \text{ kg}_{\text{EtOH}}/\text{kg}_S$

**Theoretical CO<sub>2</sub> yield (TCY)** for pure hexose sugar =  $\frac{88.02 \text{ kg}_{\text{CO}_2}}{180.15 \text{ kg}_S} = 0.49 \text{ kg}_{\text{CO}_2}/\text{kg}_S$

*Biobased feedstock  
↓  
C5/C6*

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As we discussed before, the theoretical ethanol yield is also one of the important concept in the alcoholic fermentation process. So with the help of this concept we can easily estimate the theoretical ethanol yield for given feedstock material. So if you recollect, the fermentation reaction of C5 and C6 sugars are represented by using the following equation. So the first equation here, it represent the fermentation of the pentose sugar that is C5 sugar or also we can call it as a xylose which gives ethanol and CO<sub>2</sub>.

Whereas this second equation it represent the fermentation of the C6 sugar, that is hexose, and which gives ethanol and CO<sub>2</sub> as a product. And this table here it provides the important information about the specific compound and their molar mass. Since this feedstock materials are mostly a bio-based feedstock material, so it mainly consists of C5 or C6 sugars. So these molar masses of this compound would be useful while estimating the theoretical ethanol yield of a given feedstock material. So we can represent the mole and the mass balance for the fermentation of the hexose sugars in the following way.

This 180.15 kilogram of a hexose sugar, here this is the molar mass of the hexose sugars, it produces around 92.16 kilogram of ethanol. Because if you see here the molar mass of the ethanol is 46.08 into 2, because it is producing 2 moles of ethanol. So which comes out to be around 92.16 kilogram of ethanol and 2 moles of CO<sub>2</sub>. That is 44.01 kilogram per mole into 2, that is 88.02 kilogram carbon dioxide that is on the mass basis.

So simply if you have to calculate the theoretical ethanol yield. Now for the pure hexose sugar, because here we have represented this equation in the form of the hexose sugar, so that is why the theoretical ethanol yield of this pure hexose sugar would be around 92.16, that is kilogram of the ethanol which is getting produced from 180.15 kilogram of hexose-sugars. And once you take the ratio of these 2, it comes out to be 0.51 kilogram of ethanol per kilogram of sugar, since we have considered pure hexose sugars for the fermentation process.

And similarly we can calculate the theoretical carbon dioxide yield for this pure hexose sugar. And it is 88.02 kilogram of carbon dioxide divided by 180.15 kilogram of sugar. Because this much kilogram of sugar releasing around this much amount of carbon dioxide. And this theoretical CO<sub>2</sub> yield comes out to be around 0.49 kilogram of CO<sub>2</sub> per kilogram of pure hexose sugar.

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Similarly, the TEY and TCY of real biomass can be calculated from the knowledge of the C<sub>6</sub> sugar concentration in the given biomass.

$$TEY \left( \frac{kg_{EtOH}}{ton_{biomass}} \right) = C_s \left( \frac{kg_s}{ton_{biomass}} \right) \times 0.51 \left( \frac{kg_{EtOH}}{kg_s} \right)$$

$$TCY \left( \frac{kg_{CO_2}}{ton_{biomass}} \right) = C_s \left( \frac{kg_s}{ton_{biomass}} \right) \times 0.49 \left( \frac{kg_{CO_2}}{kg_s} \right)$$

$$C_s \left( \frac{kg_s}{ton_{biomass}} \right) = V_s \left( \frac{L_s}{ton_{biomass}} \right) \times \rho \left( \frac{kg_s}{L_s} \right)$$

Where, **TEY** is theoretical ethanol yield,  
**TCY** is theoretical CO<sub>2</sub> yield  
**C<sub>s</sub>** is concentration of sugars (C<sub>5</sub>/C<sub>6</sub>) in biomass,  
**V<sub>s</sub>** is volumetric conc. of sugars (C<sub>5</sub>/C<sub>6</sub>) in biomass,  
**ρ** is ethanol density (0.789 kg/L at 20 °C).  
 Subscript "s" stands for monomeric sugars (C<sub>5</sub>/C<sub>6</sub>)



So similarly the theoretical ethanol yield and the theoretical carbon dioxide yield of real biomass sample can be estimated from the knowledge of the C<sub>6</sub> sugar in the given biomass. For example, here the theoretical ethanol yield that is kilogram of ethanol per ton of the biomass, it will be estimated using these 2 terms. Because once we know the concentration of sugar in the biomass, that is say the hexose sugar concentration in the biomass, which is represented as C suffix S that is the concentration of sugar, either it is C<sub>5</sub> sugar or C<sub>6</sub> sugar, so with the help of that we can estimate the theoretical ethanol yield.

So this term here, it represents the concentration of this specific sugar in the biomass that is kilogram of sugar per ton of biomass into 0.51 kilogram of ethanol per kilogram of sugar. That we just estimated one slide back here. That is 0.51 kilogram of ethanol per kilogram of sugar that we have estimated for the pure sugar. But once we know the concentration of the specific sugar, so by just multiplying this concentration, here we can calculate the theoretical ethanol yield for specific bio-based feedstock material. Similarly we can estimate the theoretical carbon dioxide yield that is kilogram of CO<sub>2</sub> per ton of biomass.

And this term here it represents the concentration of again the sugar. Because as we know one mole of this sugar it produces around 2 moles of CO<sub>2</sub>. So once we know the concentration of this sugar and we also know the theoretical carbon dioxide yield from a pure

hexose sugar that is 0.49 and once we multiply these terms, we can calculate the theoretical carbon dioxide yield per ton of biomass. And even this concentration of sugar in a given feedstock material can be estimated, once we know the volumetric concentration of sugar in a biomass.

And this rho is the density. So with the help of that, we can calculate the concentration of sugar in the biomass. So after learning about this important concept of theoretical ethanol yield in alcoholic fermentation process, let us move on to solve one simple example.

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**Example 3.** Calculate the theoretical ethanol yield from the fermentation of a ton of sucrose. Also determine the amount of CO<sub>2</sub> produced during this process.

**Solution:**

Sucrose undergoes hydrolysis to form hexose sugars. Fermentation of hexose results in ethanol and CO<sub>2</sub>.

The chemical equations are:

$$C_{12}H_{22}O_{11} \text{ (Sucrose)} + H_2O \xrightarrow{\text{Enzymes}} C_6H_{12}O_6 \text{ (Glucose)} + C_6H_{12}O_6 \text{ (Fructose)}$$

$$C_6H_{12}O_6 \text{ (Hexose)} \xrightarrow{28-32^\circ C; \text{Yeast (anaerobic)}} 2C_2H_5OH \text{ (Ethanol)} + 2CO_2$$

Given: 1 ton of sucrose.

From the mass balance, 1 mole sucrose (342 g/mol) produce 2 mole hexose sugar (360 g/mol).

Therefore, 1 ton of sucrose produce =  $360/342 * 1 = 1.0526$  ton of hexose sugar.

Thus, C<sub>6</sub> sugar concentration in biomass (sucrose):  $C_s = 1.0526 \text{ ton/ton} = 1052.6 \text{ kg/ton}$

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So here we can calculate the theoretical ethanol yield from the fermentation of a ton of sucrose. So here the source material is given as sucrose and also determine the amount of carbon dioxide getting produced during this process. So for this source material we need to estimate the theoretical ethanol yield as well as the carbon dioxide which is getting produced during this alcoholic fermentation process.

So we know the sucrose, once the sucrose undergoes the hydrolysis process then it forms hexose sugars. And then fermentation of this hexose sugar, it results into the formation of ethanol and carbon dioxide as a product. So as we know the hydrolysis of sucrose gives hexose sugar that is glucose and fructose. And the fermentation of the hexose sugar, here it

results into the formation of ethanol and CO<sub>2</sub> as a product. Since the given value here is one ton of sucrose, so for one ton of sucrose we need to estimate the ethanol yield as well as the carbon dioxide, which is getting generated during this alcoholic fermentation process.

So from the mass balance, here one mole of sucrose that is 342 gram per mole and this value we have obtained from the previous table, produces 2 moles of hexose sugar right and that comes out to be around 360 gram per mole. Therefore one ton of sucrose produces around 1.0526 ton of hexose sugar and thus the concentration of this hexose sugar in the biomass.

If you can just estimate, then it comes out to be around 1052.6 kilogram per ton of sucrose. Here simply we have just converted this ton to a kilogram.

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To calculate theoretical ethanol yield (TEY):

$$TEY \left( \frac{kg_{EtOH}}{ton_{biomass}} \right) = C_S \left( \frac{kg_S}{ton_{biomass\ sucrose}} \right) \times 0.51 \left( \frac{kg_{EtOH}}{kg_S} \right)$$

$$TEY = 1052.6 \text{ kg}_S / \text{ton}_{biomass\ sucrose} \times 0.51 \text{ kg}_{EtOH} / \text{kg}_S = 536.84 \text{ kg}_{EtOH} / \text{ton}_{biomass\ sucrose}$$

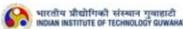
Therefore, theoretical ethanol yield of a ton of sucrose is 536.84 kg.

To determine the amount of CO<sub>2</sub> produced during the fermentation of 1 ton of sucrose:

$$TCY \left( \frac{kg_{CO_2}}{ton_{biomass\ sucrose}} \right) = C_S \left( \frac{kg_S}{ton_{biomass\ sucrose}} \right) \times 0.49 \left( \frac{kg_{CO_2}}{kg_S} \right)$$

$$TEY = 1052.6 \text{ kg}_S / \text{ton}_{biomass\ sucrose} \times 0.49 \text{ kg}_{CO_2} / \text{kg}_S = 515.77 \text{ kg}_{CO_2} / \text{ton}_{biomass\ sucrose}$$

Therefore, theoretically 515.77 kg of CO<sub>2</sub> will be produced during the fermentation of 1 ton of sucrose.

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Now, to calculate this theoretical ethanol yield, we know the theoretical ethanol yield, that is kilogram of ethanol per ton of biomass equal to sugar concentration that is kilogram of sugar per ton of biomass, into 0.51, that is the theoretical ethanol yield for the pure sugar. And this indicates the concentration of the sugar in the per ton of sucrose. So instead of writing here the biomass we can mention it as sucrose. And this value we know that is 1052.6 kilogram of sugar per ton of sucrose into 0.51 kilogram of ethanol per kilogram of sugar.

So once you multiply these two terms, the value comes out to be around 536.84 kilogram of ethanol per ton of sucrose. Therefore the theoretical ethanol yield of a ton of sucrose is 536.84 kilogram. And similarly, we can calculate the amount of CO<sub>2</sub> which is getting produced during this fermentation of 1 ton of sucrose.

That is theoretical carbon dioxide yield is represented in this form. And this value is already estimated in the example. And this is the theoretical carbon dioxide yield for a pure sugar. And once you multiply these two terms will get the value in the form of 515.77 kilogram of CO<sub>2</sub> per ton of sucrose. Therefore theoretically 515.77 kilogram of carbon dioxide will be produced during the fermentation of 1 ton of sucrose. So let us move on to the next example.

**(Refer slide time: 44:44)**

**Example 4.** In the production of ethanol, the feedstock high in sugar content is first converted to glucose<sup>C6</sup> which is then fermented into ethanol. Consider the feedstock at 100 kg/h of sugar beet roots whose sugar content represents 30% of total mass. How much maximum power can an ethanol fueled internal combustion engine produce, if the thermal efficiency of the engine at this maximum power is 38 percent? (Heat of combustion of ethanol = 26.9 MJ/ kg)

**Solution:**

Given: 100 kg of biomass, with sugar concentration,  $C_s = 30\% = 30 \text{ kg}_s / 100 \text{ kg}_{\text{biomass}} = 0.3 \text{ kg}_s / \text{kg}_{\text{biomass}}$

Theoretical ethanol yield:  $TEY \left( \frac{\text{kg}_{\text{EtOH}}}{\text{ton}_{\text{biomass}}} \right) = C_s \left( \frac{\text{kg}_s}{\text{ton}_{\text{biomass}}} \right) \times 0.51 \left( \frac{\text{kg}_{\text{EtOH}}}{\text{kg}_s} \right)$

$\therefore TEY = 0.3 \times 0.51 = 0.153 \text{ kg}_{\text{EtOH}} / \text{kg}_{\text{biomass}}$

Thus, 100 kg/h of sugar beet root can produce =  $0.153 \text{ kg}_{\text{EtOH}} / \text{kg}_{\text{biomass}} \times 100 \text{ kg}_{\text{biomass}} / \text{h} = 15.3 \text{ kg}_{\text{Ethanol}} / \text{h}$

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So here, in the production of the ethanol, the feedstock high in sugar content is first converted into glucose that is C<sub>6</sub> sugar which is then fermented into ethanol. Consider the feedstock at 100 kilogram per hour of sugar beet whose sugar content represent around 30% of total mass. How much maximum power can be ethanol fuel internal combustion engine produce, if the thermal efficiency of the engine at this maximum power is 38%? That means the thermal efficiency of the engine is 38% and the heat of combustion of ethanol is given as 26.9 megajoule per kilogram.

So with the help of this given information we need to estimate how much maximum power the ethanol fuel internal combustion engine produces if the thermal efficiency is given as 38%. Let us begin with the solution of this example here. So as we know here the 100 kilogram of biomass with sugar concentration of 30% that is 30 kilogram of sugar per 100 kg of biomass, and it comes out to be around 30 kg sugar per kg of biomass and that is the sugar concentration. And the theoretical ethanol yield, as we know theoretical ethanol yield equal to concentration of sugar into 0.51 that is kilogram of ethanol per kilogram of the pure sugar. So if we substitute this value of concentration of sugar, here we will get the theoretical ethanol yield as 0.153 kilogram of ethanol per kilogram of biomass.

However, in this example the feedstock is given as bit root sugar and that is at 100 kg per hour. So at 100 kg per hour of the sugar beet root, it can produce around this much amount of ethanol per hour that is simply we can use this theoretical ethanol yield value and we can multiplied by the 100 kg of sugar beet, that is a mass of feedstock per hour. And after this simple multiplication, the value comes out to be around 15.3 kilogram of ethanol per hour. So it means here 100 kg per hour of sugar bit root can produce 15.3 kilogram ethanol per hour. Because in this case the theoretical ethanol yield of the specific given feedstock material is 0.153 per kg of biomass. So, based on that for 100 kg of sugar bit root it produces around 15.3 kilogram of ethanol per hour.

**(Refer slide time: 48:17)**

To calculate maximum power can be produced by ethanol fueled internal combustion engine:

Thermal efficiency of the engine = 38%

Heat of combustion of ethanol = 26.9 MJ/kg

Ethanol produced = 15.3 kg Ethanol/h

Maximum power can be produced =  $15.3 \text{ kg}_{\text{Ethanol}}/\text{h} \times 26.9 \text{ MJ/kg} \times 0.38$

= 156.4 MJ/h

= 156.4 MJ/h

=  $156.4 \frac{\text{MJ}}{\text{h}} \times \frac{1 \text{ h}}{60 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ s}} = 0.04344 \frac{\text{MJ}}{\text{s}} = 43.44 \frac{\text{kJ}}{\text{s}} = 43.44 \text{ kW}$

Therefore, maximum 43.44 kW of electric power can be produced.

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So after estimating this theoretical ethanol yield let us calculate the maximum power, which can be produced by ethanol fuel internal combustion engine. And here the thermal efficiency of the engine is given as 38% and the heat of combustion of the ethanol is 26.9 mega joules per kg and the ethanol produced is around 15.3 kg per hour. So the maximum power produced by ethanol fuel internal combustion engine can be estimated using the ethanol produced value that is 15.3 kilogram per hour into its heat of combustion and we know the thermal efficiency of the engine is 38%.

So once you multiply this efficiency into heat of combustion into the amount of ethanol which is getting produced, just multiplying these terms, here will get the value in the form of 156.4 mega joule per hour and now we will just try to convert this value into megawatt. So here it is 156.4 mega joule per hour, which is converted into minute and then into seconds. And once you just do this small multiplication, here the value comes out to be around 0.043 double 4 mega joule per second.

So this mega joule per second can be converted into 43.44 kilo joule per second and this is 43.44 kilowatt. So 1 kilo joule per second is equal to 1 kilowatt. So, maximum power which can be produced by ethanol fuel internal combustion engine is around 43.44 kilowatt. And therefore the maximum 43.44 kilowatt of electrical power can be produced.

**(Refer slide time: 50:30)**

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And these are the references which are used for this specific lecture. You can make a note of this and if required you can take the help of these references also, while solving this example as well as while solving the other example for the different feedstock materials. I hope now this is clear how to go for the sizing of the digester in a anaerobic digestion process as well as how to calculate the theoretical ethanol yield for the real biomass sample in a alkali fermentation process. So the next lecture that will be the first lecture of the module 6, we will discuss about chemical conversion processes, types of feedstock, biodiesel production processes and different extraction processes.

Thank you.