Fundamentals of Combustion for Propulsion

Dr. S Varunkumar
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture- 09

Quenching, flammability and other limit phenomena

Welcome back. In this lecture we will discuss limit phenomena, specifically flammability limits and quenching distance. And, we will also look at the phenomena of ignition, a couple of simple relationship relations that we derived in one of the earlier lectures connecting the reaction rate and flame speed and flame thickness will be required for the discussions today.

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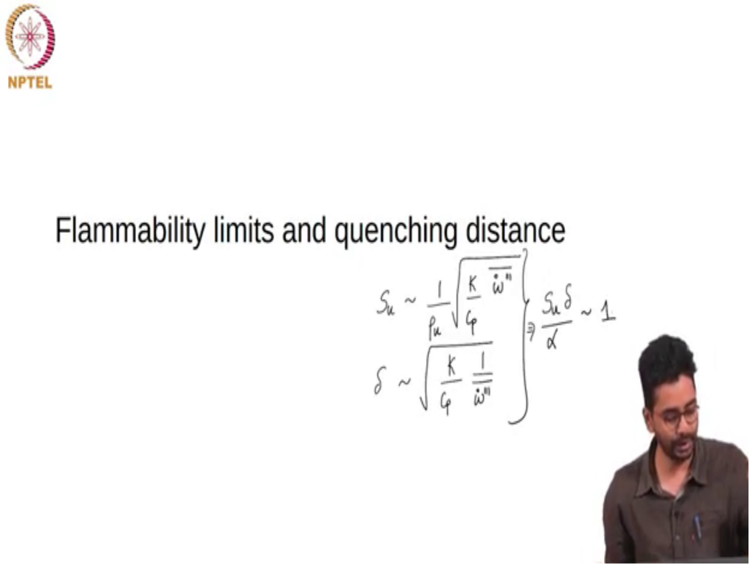

Flammability limits and quenching distance

$$\left.\begin{aligned} S_u &\sim \frac{1}{\rho_u}\sqrt{\frac{K}{c_p}\overline{\dot{\omega}'''}} \\ \delta &\sim \sqrt{\frac{K}{c_p}\frac{1}{\overline{\dot{\omega}'''}}} \end{aligned}\right\} \Rightarrow \frac{S_u \delta}{\alpha} \sim 1$$

Just to recall, we derived this equation that the flame speed goes as 1 over rho u K by c p omega dot triple dash averaged square root. And, thickness of the flame or a measure of the thickness of the flame would be K over c p 1 divided by omega dot triple dash averaged square root ok; combined this implies that S u delta over alpha is of order 1 ok. We will need these equations in today's lecture.

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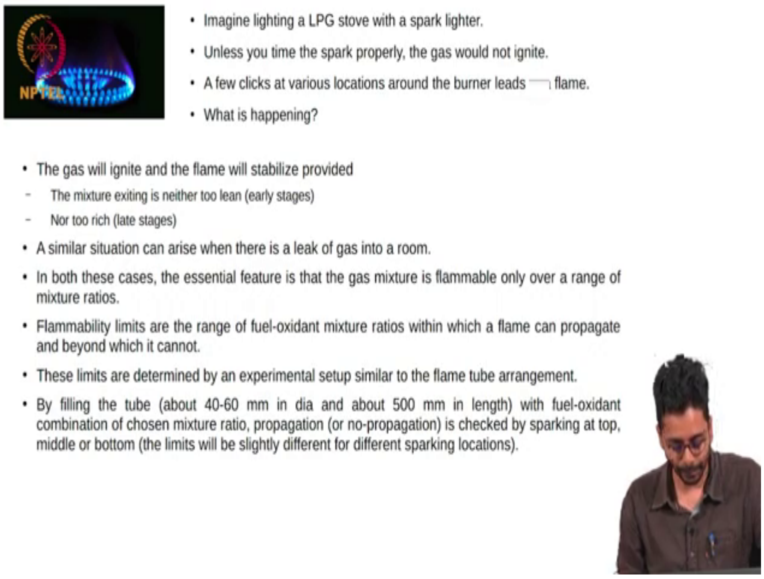

- Imagine lighting a LPG stove with a spark lighter.
- Unless you time the spark properly, the gas would not ignite.
- A few clicks at various locations around the burner leads flame.
- What is happening?

- The gas will ignite and the flame will stabilize provided
  - The mixture exiting is neither too lean (early stages)
  - Nor too rich (late stages)
- A similar situation can arise when there is a leak of gas into a room.
- In both these cases, the essential feature is that the gas mixture is flammable only over a range of mixture ratios.
- Flammability limits are the range of fuel-oxidant mixture ratios within which a flame can propagate and beyond which it cannot.
- These limits are determined by an experimental setup similar to the flame tube arrangement.
- By filling the tube (about 40-60 mm in dia and about 500 mm in length) with fuel-oxidant combination of chosen mixture ratio, propagation (or no-propagation) is checked by sparking at top, middle or bottom (the limits will be slightly different for different sparking locations).

So, what is what are flammability limits? A good example: to work with this domestic LPG flame. So, imagine lighting an LPG stove with a spark lighter, unless you time the spark properly, the gas would not ignites. A few clicks at various locations around the burner leads to a flame. So, in this situation what is happening? So, the gas will ignite and the flame will stabilize provided the mixture that is exiting the burner, this is a mixture of LPG and air is neither too lean which would be the case in the early stages when you open the valve nor too rich which would be the case when you wait too long to ignite.

A similar situation can arise when there is a leak of gas in two room, in both these cases the essential feature is that the gas mixture is flammable only over a range of mixture ratios; too lean it could not ignite, too rich it would not ignite. So, it has to be within a certain range for it to ignite. So, this these limits are the flammability limits.

So, flammability limits are the range of fuel oxidant mixture ratios within which a flame can propagate and beyond which it cannot. These limits are determined by an experimental setup which is very similar to the flame tube arrangement. A video of which we saw in one of the earlier lectures, you have a long cylindrical tube of about 50 millimeters in diameter, filled with premixed mixture of fuel and oxidizer.

The experiment we saw was in fact, a mixture of LPG and air of three different equivalence ratios; lean, close to stoichiometric and rich, ignition is ignition is done by a spark at one end and we saw reaction front that propagates into the unburned mixture. So, the experimental setup for determining the flammability limits are essentially the same ah.

So, by filling the tube of diameter about 40 to 60 millimeters and about 500 millimeters in length with fuel oxidant combination of chosen mixture ratio, propagation or no propagation is checked by sparking at three locations; top, middle or bottom. The limits will depend on whether the ignition is at the top, middle or bottom.

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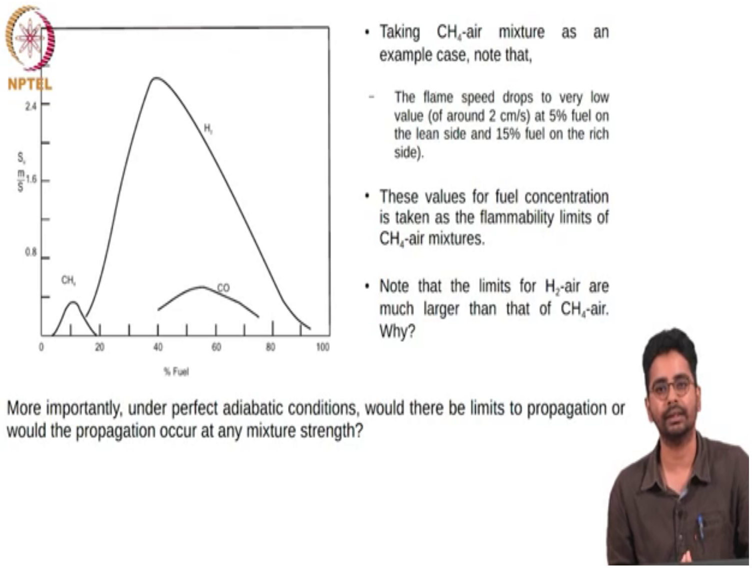

- Taking CH_4-air mixture as an example case, note that,
  - The flame speed drops to very low value (of around 2 cm/s) at 5% fuel on the lean side and 15% fuel on the rich side).
- These values for fuel concentration is taken as the flammability limits of CH_4-air mixtures.
- Note that the limits for H_2-air are much larger than that of CH_4-air. Why?

More importantly, under perfect adiabatic conditions, would there be limits to propagation or would the propagation occur at any mixture strength?

So, by this experimental procedure flammability limits have been experimentally determined for a variety a fuel oxidizer mixtures. Let us take methane air mixture for example, the flame speed as you can see in the plot on the left hand side. The flame speed drops to a very low value of about 2 centimeters per second at 5 percent fuel on the lean side. And, also though about 2 centimeters per second at 15 percent fuel on the rich side.

These values for fuel concentration are taken as the flammability limits of methane air mixtures. It is 5 percent methane, 95 percent air on the lean side anything, fuel percentage lower than that a flame will not propagate. On the rich side it has 15 percent methane, 85 percent air, more fuel it is this mixture that is richer than that the flame will not propagate.

Remember that stoichiometric methane air mixture is about 9.5 percent methane and rest is air ok. So, these values for fuel concentration are taken as a flammability limits of methane air mixtures. Note that the limits for hydrogen air are much larger than that of CH 4 air. I would like you to think about this question based on the relationship between flame speed reactivity and other properties, that we discussed in the earlier lectures.

An important fundamental question is under perfect adiabatic conditions; so, no heat loss, let us say in the hypothetical case where we are even able to exclude or prevent heat loss by radiation from the flame. The question is would there be limits to propagation or they would or would the propagation occur at all mixture strengths? The question that we are asking is, is the flammability limit simply consequence of the presence of heat losses in real experimental setups?

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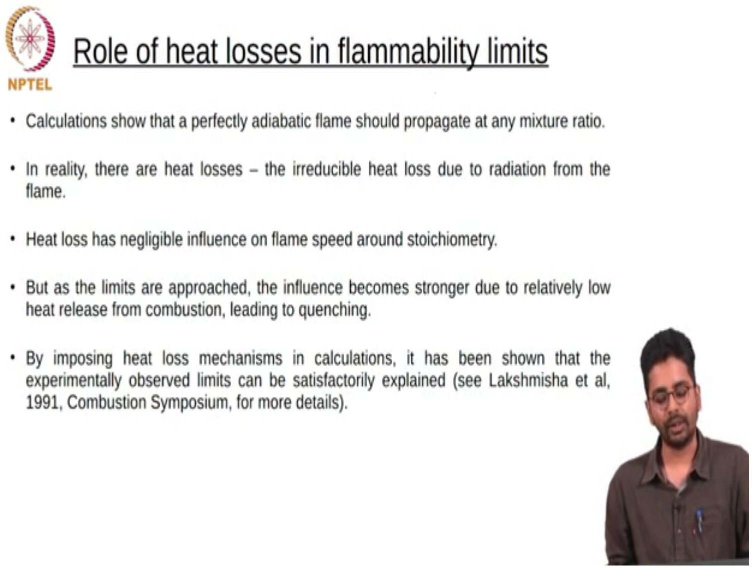

Role of heat losses in flammability limits

- Calculations show that a perfectly adiabatic flame should propagate at any mixture ratio.
- In reality, there are heat losses – the irreducible heat loss due to radiation from the flame.
- Heat loss has negligible influence on flame speed around stoichiometry.
- But as the limits are approached, the influence becomes stronger due to relatively low heat release from combustion, leading to quenching.
- By imposing heat loss mechanisms in calculations, it has been shown that the experimentally observed limits can be satisfactorily explained (see Lakshmisha et al, 1991, Combustion Symposium, for more details).

So, what is the role of heat losses in flammability limits? Calculations of flame propagation show that a perfectly adiabatic flame should propagate at any mixture ratio. But, in reality there are always heat losses, even if we managed to prevent conductive heat losses; the irreducible heat loss due to radiation from the flame is always there ok. Heat loss in general has negligible influence on the flame speed around stoichiometric. For example, accounting for heat loss will change the flame speed at stoichiometric conditions by less than 2 percentage.

But, as the limits of flammability are approached, the influence becomes stronger due to relatively low heat release from combustion leading to quenching. By imposing heat loss mechanisms in calculations, it has been shown that the experimentally observed limits can be satisfactorily explained indicating that the observed in the experimentally observed flammability limits are sensitive to heat loss from the system.

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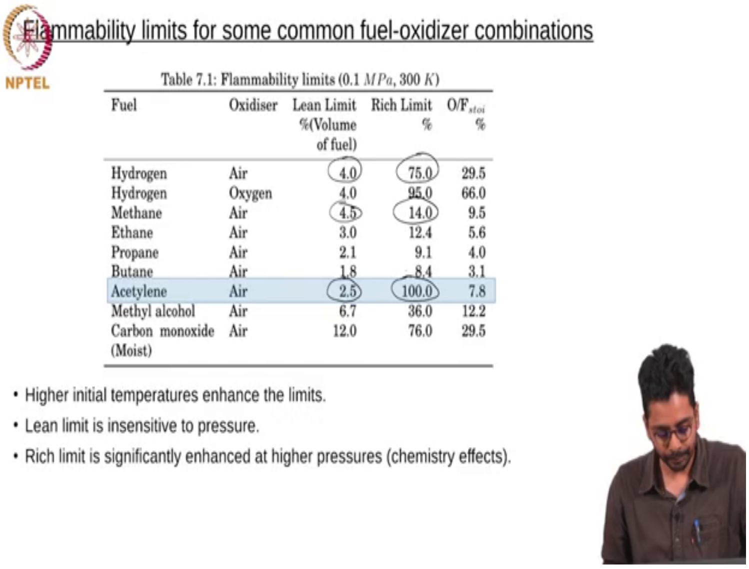

Flammability limits for some common fuel-oxidizer combinations

Table 7.1: Flammability limits (0.1 MPa, 300 K)

Fuel	Oxidiser	Lean Limit %(Volume of fuel)	Rich Limit %	O/F_{stoi} %
Hydrogen	Air	4.0	75.0	29.5
Hydrogen	Oxygen	4.0	95.0	66.0
Methane	Air	4.5	14.0	9.5
Ethane	Air	3.0	12.4	5.6
Propane	Air	2.1	9.1	4.0
Butane	Air	1.8	8.4	3.1
Acetylene	Air	2.5	100.0	7.8
Methyl alcohol	Air	6.7	36.0	12.2
Carbon monoxide (Moist)	Air	12.0	76.0	29.5

- Higher initial temperatures enhance the limits.
- Lean limit is insensitive to pressure.
- Rich limit is significantly enhanced at higher pressures (chemistry effects).

In this table flammability limits are shown for some common fuel oxidizer combinations at an initial pressure of 1 bar and an initial temperature of 300 Kelvin’s. We already saw the case of methane which is the lean limit is about four and a half percent methane and the rich limit is 14 percent methane. An interesting hydrogen we saw has wide the flammability limits, lean limit is 4 percent hydrogen, rich limit is 75 percent hydrogen.

An interesting fuel is acetylene, the lean limit is about two and a half percent acetylene, the rich limit is 100 percent. This is because acetylene can exothermically decompose and form a flame even in the absence of air. So, questions similar to what we asked about flame speed can also be asked about flammability limits; what is the effect of initial temperature and what is the effect of initial pressure and so on.

Of course, higher initial temperatures enhance the limits, the dependence simply through the change in the flame temperature and the reaction rate. Lean limit seems insensitive to pressure, but rich limit is significantly enhanced at higher pressures. This is because of kinetic effects ok.

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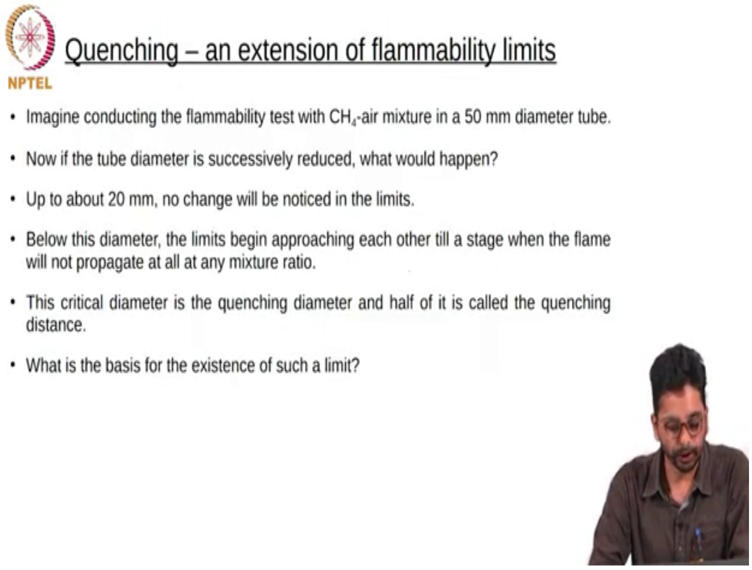

Quenching – an extension of flammability limits

- Imagine conducting the flammability test with CH_4-air mixture in a 50 mm diameter tube.
- Now if the tube diameter is successively reduced, what would happen?
- Up to about 20 mm, no change will be noticed in the limits.
- Below this diameter, the limits begin approaching each other till a stage when the flame will not propagate at all at any mixture ratio.
- This critical diameter is the quenching diameter and half of it is called the quenching distance.
- What is the basis for the existence of such a limit?

Next we will move on to the idea of quenching which is simply an extension of flammability limits. The experimental setup that is used for measuring flammability limits is as I described is cylindrical tube of about 50 millimeters diameter and 500 millimeters in length. Imagine conducting a test of flammability test with methane air mixture and such a tube. And, now if the tube diameter is reduced successively, what would happen? Experiments indicate that up to about 20 millimeters, there is a significant change in the measured limits.

But as the diameter goes below 20 millimeters below this diameter, the limits begin approaching each other till a stage when the flame will not propagate at all at any mixture ratio. This critical diameter at which the flame even a stoichiometric mixture cannot actually have a propagating flame is known as the quenching diameter and half of this value is called quenching distance. So, what is the basis for the existence of such a limit?

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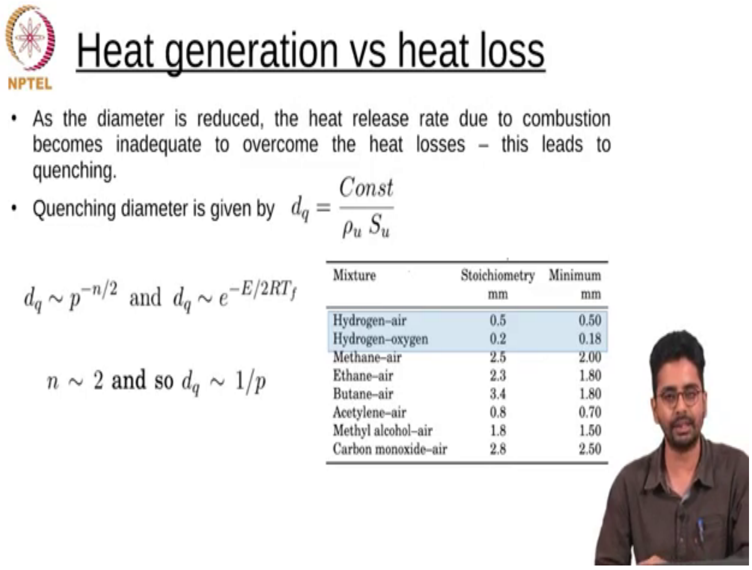

Heat generation vs heat loss

- As the diameter is reduced, the heat release rate due to combustion becomes inadequate to overcome the heat losses – this leads to quenching.
- Quenching diameter is given by $d_q = \dfrac{Const}{\rho_u \, S_u}$

$$d_q \sim p^{-n/2} \text{ and } d_q \sim e^{-E/2RT_f}$$

$$n \sim 2 \text{ and so } d_q \sim 1/p$$

Mixture	Stoichiometry mm	Minimum mm
Hydrogen–air	0.5	0.50
Hydrogen–oxygen	0.2	0.18
Methane–air	2.5	2.00
Ethane–air	2.3	1.80
Butane–air	3.4	1.80
Acetylene–air	0.8	0.70
Methyl alcohol–air	1.8	1.50
Carbon monoxide–air	2.8	2.50

It is a simple as the diameter is reduced, the heat release rate due to combustion becomes inadequate to overcome the heat losses and this leads to quenching. So, the quenching diameter is dependent on the flame speed, maybe I will show how this comes about.

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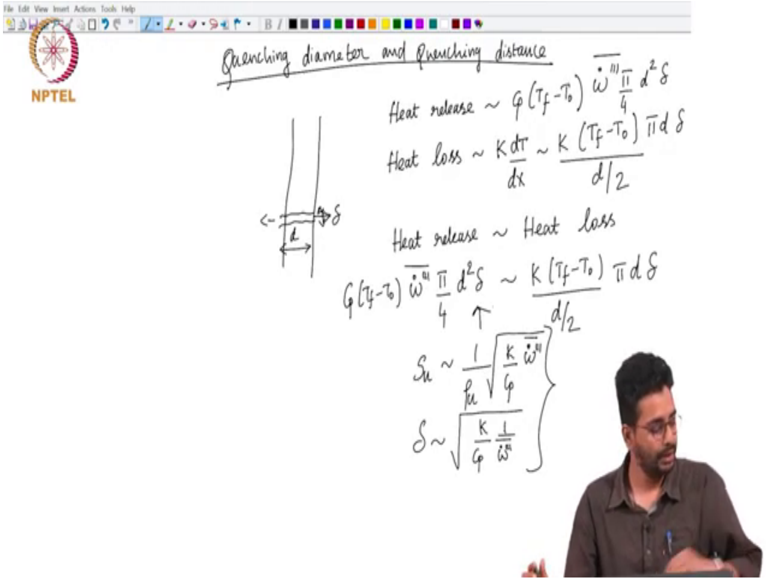

Quenching diameter and Quenching distance

$$\text{Heat release} \sim C_p (T_f - T_0)\, \overline{\dot{\omega}'''}\, \frac{\pi}{4} d^2 \delta$$

$$\text{Heat loss} \sim K \frac{dT}{dx} \sim \frac{K (T_f - T_0)}{d/2} \pi d \delta$$

$$\text{Heat release} \sim \text{Heat loss}$$

$$C_p (T_f - T_0)\, \overline{\dot{\omega}'''}\, \frac{\pi}{4} d^2 \delta \sim \frac{K (T_f - T_0)}{d/2} \pi d \delta$$

$$\left.\begin{array}{l} S_u \sim \dfrac{1}{\rho_u} \sqrt{\dfrac{K}{C_p} \overline{\dot{\omega}'''}} \\ \delta \sim \sqrt{\dfrac{K}{C_p} \dfrac{1}{\overline{\dot{\omega}'''}}} \end{array}\right\}$$

We are looking at flame propagating in a tube, flame has a thickness of delta, the tube diameter is d ok. So, heat released because of combustion we know is C p T f minus T 0 which is the enthalpy of the combustion which rises the temperature of the mixture from initial temperature to the flame temperature multiplied by the rate of the reaction, multiplied by the volume of the reaction zone which is pi by 4 d squared times delta ok.

So, this is the heat release because of chemical reactions. The heat loss is because of heat loss from the sides ok, from the flame to the walls and to the ambient. The heat losses K d T d x which is approximately in this case K T f minus T 0 over d by 2; this is the gradient and the radial direction. So, the flame will quench, the flame will steadily propagate when heat release is much higher than the heat loss.

And, in the limiting case when heat release becomes comparable to heat loss, the flame cannot propagate anymore because the heat that is released is not sufficient to sustain propagation. So, under these conditions we will have C p T f minus T 0 delta K; the term on the left hand side is has units of energy, the term on the right hand side has units of flux. So, I should multiply this by the area which would be pi d delta ok.

Now, starting from here and making use of the relationship that we have already derived between flame speed and reaction rate, remember this. And, delta going as K by C p 1 over omega dot triple dash square root, make use of these two expressions to eliminate reaction rate and delta from this equation; you will arrive at an expression that I have shown in the slides.

So, quenching diameter is inversely proportional to the flame speed and we already know that we already know the pressure and the initial temperature dependence of flame speed. So, flame speed goes if flame speed is not very sensitive to pressure for bi molecular reactions; for most fuel oxidizer combinations the flame speed is insensitive to pressure. And, the density goes as 1 over pressure, this gives a dependence that goes like this; the quenching diameter goes as pressure rise to minus n by 2, n is about 2.

So, the quenching distance goes inversely as pressure and the dependence on temperature is through the Arrhenius term. So, the quenching diameter goes as exponential minus E twice RT f ok. So, n is typically 2, bi molecular reactions and therefore, quenching distance goes is 1 over pressure. Let us look at some typical values for the quenching distance, remember that more reactive the fuel is higher is the flame speed and therefore, smaller is the quenching distance.

So, we know that hydrogen air is very reactive is more reactive than methane air and a stoichiometric mixture of hydrogen air has a quenching distance of about half mm. Hydrogen oxygen is more reactive than hydrogen air, the quenching distance is as small as 0.2

millimeters that is 200 micron ok. Methane air not so reactive, the methane air is not so reactive, has a quenching diameter of about 2.5 millimeters.

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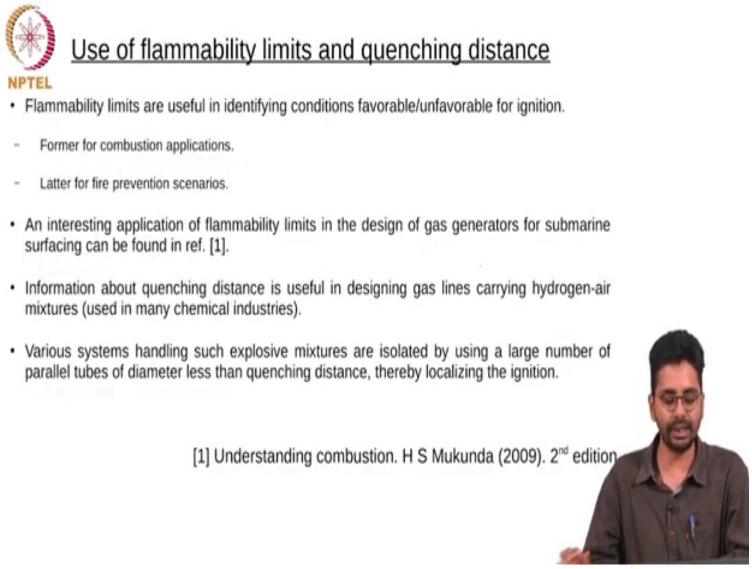

Use of flammability limits and quenching distance

- Flammability limits are useful in identifying conditions favorable/unfavorable for ignition.
  - Former for combustion applications.
  - Latter for fire prevention scenarios.
- An interesting application of flammability limits in the design of gas generators for submarine surfacing can be found in ref. [1].
- Information about quenching distance is useful in designing gas lines carrying hydrogen-air mixtures (used in many chemical industries).
- Various systems handling such explosive mixtures are isolated by using a large number of parallel tubes of diameter less than quenching distance, thereby localizing the ignition.

[1] Understanding combustion. H S Mukunda (2009). 2nd edition

So, what is the use of flammability limits and quenching distance? Flammability limits are useful in identifying conditions which are favorable or unfavorable for ignition. We need favorable conditions for ignition, for combustion applications where we want a steady flame. And we do not need favorable conditions for ignition; when we want to prevent combustion from happening like in fire scenarios, fire prevention scenarios.

Another interesting application of flammability limits is in the design of gas generators for submarine surfacing. This is an interesting case study that is a brief explanation of this is given in reference 1, where a mixture of hydrazine and where hydrazine is used in a gas generator to actually generate gases required for resurfacing of, fast resurfacing of submarines. Information about quenching distance is useful in designing gas lines carrying hydrogen air mixture is used in many chemical industries.

What is done in such places handling explosive mixtures is that systems, various systems handling explosive mixtures are isolated by using a large number of parallel tubes of diameter less than the quenching distance. Therefore, even if there is ignition in one of these systems, the flame is or the ignition is localized to that system. And, the fact that the pipes connecting these various systems have a cross section that is smaller than the quenching distance, it will prevent the flame from propagating from one block to the other block thereby, localizing the ignition ok.

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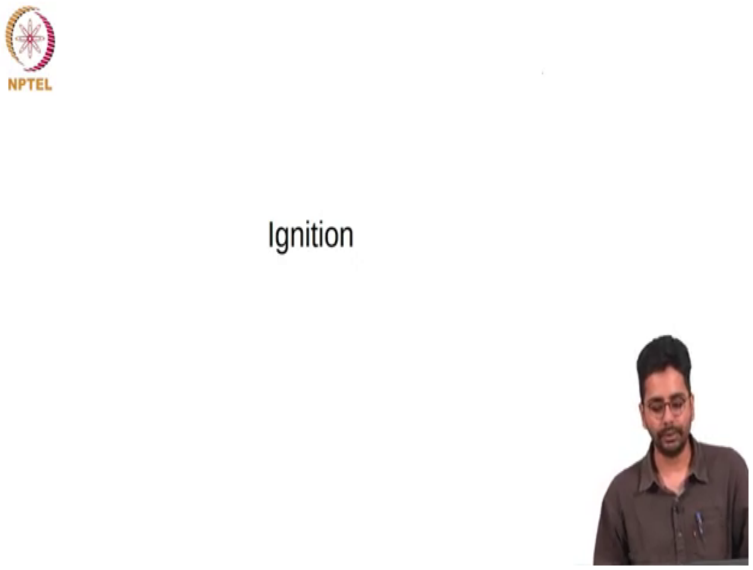

Ignition

So, that concludes the discussion on flammability limits and quenching, let us move on to ignition.

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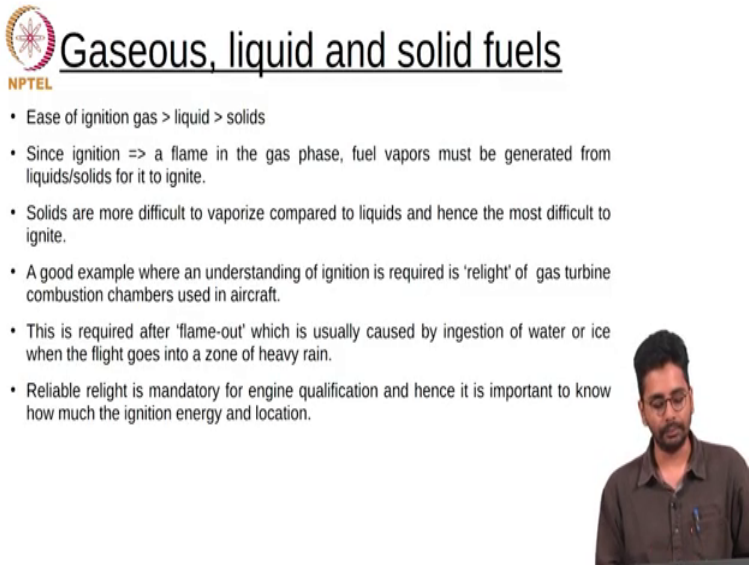

Gaseous, liquid and solid fuels

- Ease of ignition gas > liquid > solids
- Since ignition => a flame in the gas phase, fuel vapors must be generated from liquids/solids for it to ignite.
- Solids are more difficult to vaporize compared to liquids and hence the most difficult to ignite.
- A good example where an understanding of ignition is required is 'relight' of gas turbine combustion chambers used in aircraft.
- This is required after 'flame-out' which is usually caused by ingestion of water or ice when the flight goes into a zone of heavy rain.
- Reliable relight is mandatory for engine qualification and hence it is important to know how much the ignition energy and location.

Ignition the effort required for ignition is different for gaseous, liquid and solid fuels; this we know from experience. So, the in terms of ease of ignition its easiest to ignite gases or mixtures, reactive gaseous mixtures followed by liquids followed by solids ok. Ignition implies what we mean when we say that something is ignited that a flame is established in the gas phase, a self sustaining flame is established in the gas phase. And therefore, fuel vapors must be generated from liquids or solids for it to ignite.

In the case of gaseous mixtures we already have the fuel air mixture in the gaseous form, but in liquids and solids energy must be provided to vaporize the liquid or decomposed solid to generate enough amounts of vapors; for a gaseous flame to be established. Solids as we know are more difficult to vaporize compared to liquids and hence the most difficult to ignite. This even includes very reactive fuels like rocket fuels. Enormous amount of energy compared to gaseous fuels is required to ignite solid propellant rockets for example.

A good example where an understanding of ignition is required is the situation called relight of gas turbine combustion chamber is used in aircraft. This is required after what is called flame out which is usually caused when an aircraft goes through a region of heavy rain or hail and lot of water or ice particles go into the engine combustion chamber quenching the flame ok. Reliable relight is under these very difficult conditions is mandatory for engine qualification and hence it is important to know the criteria for ignition under such conditions. Quantified in terms of ignition energy and where these energy must be provided.

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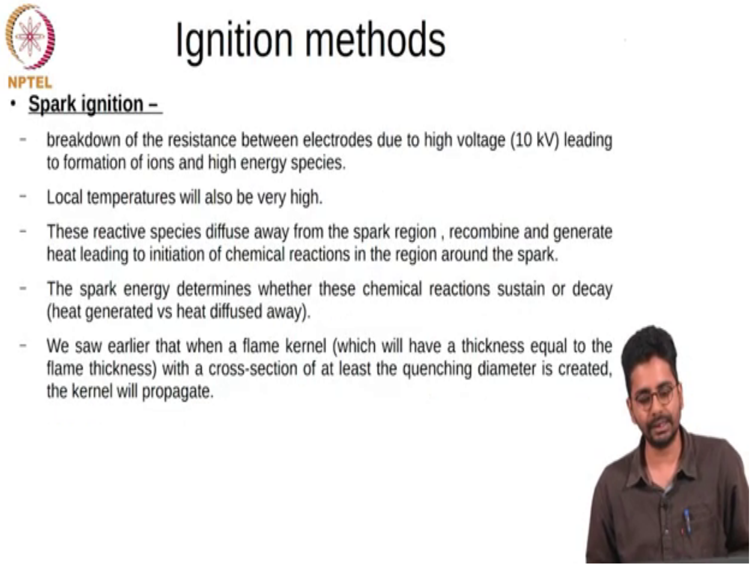

Ignition methods

- **Spark ignition –**
  - breakdown of the resistance between electrodes due to high voltage (10 kV) leading to formation of ions and high energy species.
  - Local temperatures will also be very high.
  - These reactive species diffuse away from the spark region , recombine and generate heat leading to initiation of chemical reactions in the region around the spark.
  - The spark energy determines whether these chemical reactions sustain or decay (heat generated vs heat diffused away).
  - We saw earlier that when a flame kernel (which will have a thickness equal to the flame thickness) with a cross-section of at least the quenching diameter is created, the kernel will propagate.

So, ignition methods: the most common ignition method is the spark ignition; breakdown of resistance between electrodes due to high voltage leads to formation of plasma ions and high energy species in this localized zone. The local temperatures will also be very high. These reactive species diffuse away from the spark region, we combine and generate heat leading to initiation of chemical reactions in the region around this spark.

The energy of the spark must be sufficient to sustain the flame propagation. So, the spark energy determines whether these chemical reactions sustain or decay away. If the energy is less than a critical value locally there will be ignition, but there will not be enough energy for the flame to propagate and ignite the surrounding mixture and the entire process would get killed.

Therefore, there is a certain minimum amount of energy that is required to make sure that whatever is ignited is sufficient to sustain the process. We saw earlier in the context of quenching distance that when a flame kernel that is a piece of flame which will have a thickness equal to the flame thickness and with a cross section of at least the quenching diameter is generated, that flame kernel can propagate on its own.

Because, the heat release within such flame kernel is higher than the heat loss and therefore, propagation can occur starting from that situation. If we create a flame kernel which has a diameter or a cross section that is smaller than the quenching distance, losses are losses overcome the heat release and the propagation will cease. So, this simple criteria which we used to derive the quenching distance can also be used to calculate the minimum ignition energy.

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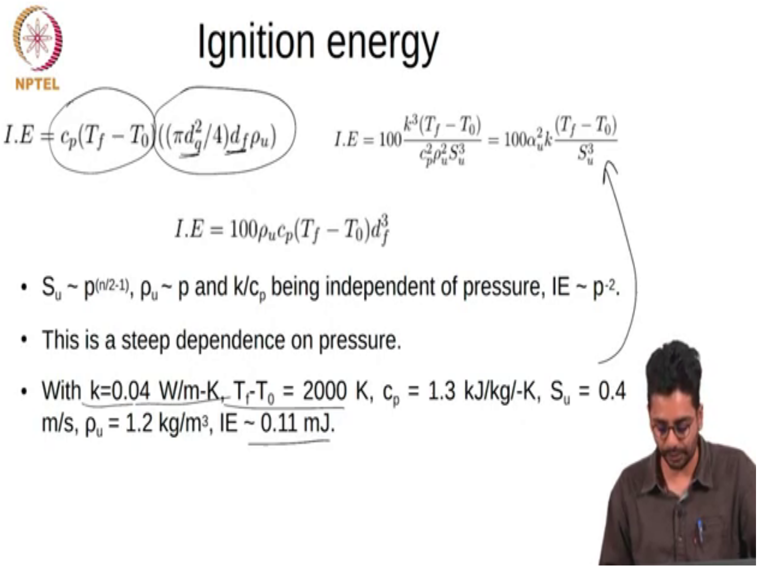

Ignition energy

$$I.E = c_p(T_f - T_0)((\pi d_q^2/4)d_f\rho_u) \qquad I.E = 100\frac{k^3(T_f - T_0)}{c_p^2\rho_u^2 S_u^3} = 100\alpha_u^2 k\frac{(T_f - T_0)}{S_u^3}$$

$$I.E = 100\rho_u c_p(T_f - T_0)d_f^3$$

- $S_u \sim p^{(n/2-1)}$, $\rho_u \sim p$ and k/c_p being independent of pressure, IE ~ p^{-2}.
- This is a steep dependence on pressure.
- With k=0.04 W/m-K, T_f-T_0 = 2000 K, c_p = 1.3 kJ/kg/-K, S_u = 0.4 m/s, ρ_u = 1.2 kg/m^3, IE ~ 0.11 mJ.

That is exactly what is done here. The ignition energy is simply the energy that is required to create a flame kernel. Remember that the energy is the temperature should rise from the initial temperature to the flame temperature. And, the corresponding volume should be equal to flame thickness and a cross section that is at least the quenching diameter ok. So, this is the minimum ignition energy that is required for creating the flame ok.

And, now again we earlier derived an expression for the quenching distance in terms of the flame speed and we already have an expression for the flame thickness in terms of reaction rate and flame speed and so on. So, what is done here is that the same equations that we used earlier are used to express the minimum ignition energy in terms of the flame speed. Remember, that we expressed the quenching distance in terms of the flame the speed, here we are expressing the ignition energy also in terms of the flame speed ok.

So, again the same dependence is on pressure and initial temperature apply here and we know that flame speed goes as pressure raise to n by 2 minus 1, n is typically 2. So, the flame speed is insensitive to pressure. There are exceptions, but this is in general is true. Density, the unburned gas density is directly proportional to pressure and the K by c p is independent of pressure.

This makes the minimum ignition energy go as 1 over p squared. This is a very strong dependence on pressure which must be recognized, the consequences of this is something that we will see in the next slide. So, this is a very steep dependence on pressure. So, by plugging in some typical values, a thermal conductivity of 0.04 Watts per meter Kelvin, delta T of 2000 Kelvin's.

And, flame speed corresponding to a typical hydrocarbon air mixture about 40 centimeters per second. You can calculate the minimum ignition energy to about one-tenth of a milli Joules, its 0.1 milli Joule ok. All that I have done is plugged in these numbers, plugged in the numbers that are given here into this formula ok; to calculate the minimum ignition energy which turns out to be 0.1 milli Joule. It is a good number to remember, this is a minimum ignition energy required for igniting gaseous fuel air mixture.

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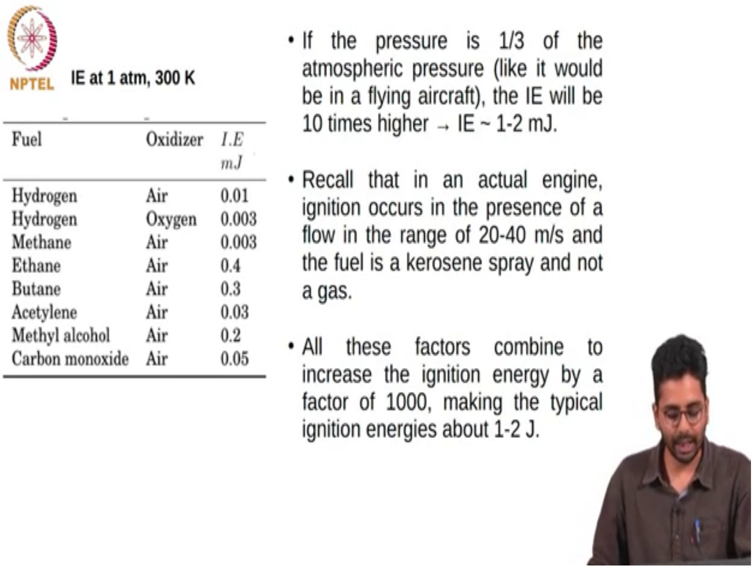

IE at 1 atm, 300 K

Fuel	Oxidizer	*I.E* *mJ*
Hydrogen	Air	0.01
Hydrogen	Oxygen	0.003
Methane	Air	0.003
Ethane	Air	0.4
Butane	Air	0.3
Acetylene	Air	0.03
Methyl alcohol	Air	0.2
Carbon monoxide	Air	0.05

- If the pressure is 1/3 of the atmospheric pressure (like it would be in a flying aircraft), the IE will be 10 times higher → IE ~ 1-2 mJ.
- Recall that in an actual engine, ignition occurs in the presence of a flow in the range of 20-40 m/s and the fuel is a kerosene spray and not a gas.
- All these factors combine to increase the ignition energy by a factor of 1000, making the typical ignition energies about 1-2 J.

Some typical values are shown here, hydrogen air is very low 0.01 milli Joules, hydrogen oxygen is even lower more reactive, methane air I think there is a probably a mistake in the a number is given here. This is this should be about 0.1 milli Joule. I will check and correct it, but the other numbers seem ok, ethane is 0.4 milli Joules, butane is 0.3 milli Joules and so on; that is typically the order of magnitude of the minimum ignition energy. What is important to recognize is that these values are all calculated at 1 atmosphere and 300 Kelvin’s.

And, now imagine that you are under conditions where the pressure has decreased by a factor of 3 compared to the atmospheric pressure; like it could be in a flying aircraft which is flying at an altitude. So, the pressure has decreased by a factor of 3, remember that the ignition energy goes as 1 over pressure squared and therefore, now the ignition energy will go up by a factor of 10. So, 0.1 milli Joules will now become 1 milli Joule, it is a factor of 10.

And, more important to remember that in an actual engine the ignition occurs or ignition should occur in the presence of a flow which is about 20 to 40 meters per second. And, in addition to this the fuel air mixture is not in a pre-prepared gaseous form, what is injected as fuel is fine droplets of kerosene which must vaporize, form the fuel air mixture and ignite in the presence of air flow which is 20 to 40 meters per second and at a pressure that is one-third of the atmospheric pressure.

All these additional things increase the minimum ignition energy required by a factor of about 1000, let me give you a break up here. Gaseous mixture, atmospheric pressure 0.1 milli Joules, gaseous mixture one-third of the atmospheric pressure; 10 times more that is 1 to 2 milli Joule. Introduction of a cross stream, introduction of air flow of 20 to 40 meters per second increases the ignition energy by a factor of 100.

And, the fact that the fuel is introduced as liquid and not as a gas introduced introduces another factor of 10. Therefore, the total increase in ignition energy from this 1 to 2 milli Joule is a factor of 1000, 100 for the flow and for the 10 for the vaporization energy required for converting liquid fuel into a gaseous fuel, makes the typical ignition energy is about 1 to 2 joules in liquid fuel systems ok.

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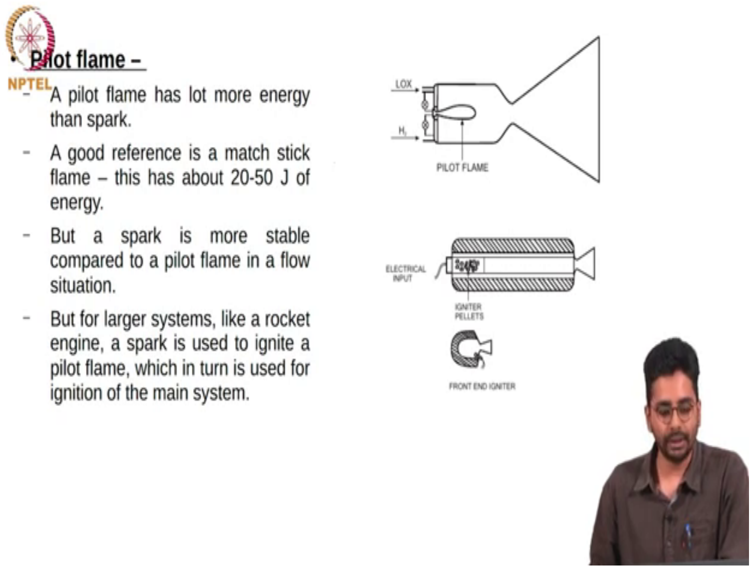

- **Pilot flame –**
  - A pilot flame has lot more energy than spark.
  - A good reference is a match stick flame – this has about 20-50 J of energy.
  - But a spark is more stable compared to a pilot flame in a flow situation.
  - But for larger systems, like a rocket engine, a spark is used to ignite a pilot flame, which in turn is used for ignition of the main system.

Another ignition method that is used is the pilot flame ignition method of course, pilot flame has lot more energy than a spark. Spark we saw as a few 100 milli Joules to a few Joules. A pilot flame will have a energy of about a few 20 to 50 Joules, a good reference is a matchstick, matchstick flame this has about 20 to 50 Joules of energy. But of course, we know that under strong flow a spark is more stable compared to a pilot flame, but it is not that pilot flames are not used. For larger systems like a rocket engines, what is done as sort of a multi stage ignition where we use where a spark is used to ignite a pilot flame.

And, then the pilot flame in turn is used for ignition of the main system; two examples are shown here. One is a cryogenic engine, a LOX H 2 engine, where a pilot flame is created by a spark; first pilot flame is created by a spark. And, then more by introducing a small amount of fuel and oxidizer into the system first.

Once the pilot flame is established, more fuel and oxidizer are introduced into the system to establish steady conditions. Another interesting example is solid rocket engine, where igniter pellets or pyrotechnic compositions are ignited using an electric spark. And, the hot particles and hot gases generated by the burning of these igniter pellets in turn ignite the rest of the rocket..

And, these are done for small solid rocket motors for space boosters, what is done is a 3 stage ignition where we have an electrical input igniting the pyrotechnic charge which will ignite a small rocket motor like the one that is shown here. And, this small rocket motor will actually go through the port of the large rocket motor spewing hot particles onto the surface of the propellant igniting the propellant. So, it is a rocket motor within a rocket motor.

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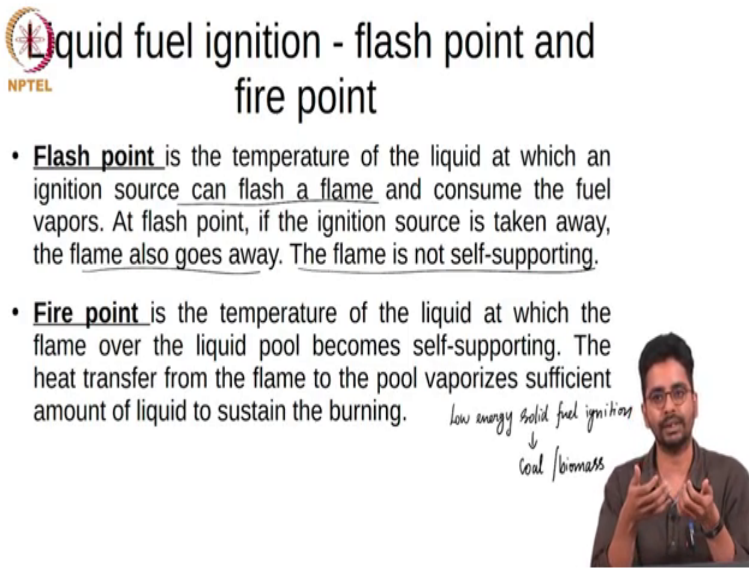

Liquid fuel ignition - flash point and fire point

- **Flash point** is the temperature of the liquid at which an ignition source can flash a flame and consume the fuel vapors. At flash point, if the ignition source is taken away, the flame also goes away. The flame is not self-supporting.
- **Fire point** is the temperature of the liquid at which the flame over the liquid pool becomes self-supporting. The heat transfer from the flame to the pool vaporizes sufficient amount of liquid to sustain the burning.

Low energy solid fuel ignition
↓
Coal / biomass

A couple of ideas that we need to know to understand liquid fuel or appreciate liquid fuel ignition is a flashpoint and the fire point. Flashpoint is the temperature of the liquid at which an ignition source can flash a flame, this is important to keep in mind that it will flash a flame and consume the vapors that were generated. But, once you remove the ignition source, the flame will go away ok. So, this flame which is created at the flashpoint is not self supporting, it is there as long as you have the ignition source; you take the ignition source the flame goes away.

On the other hand fire point is the temperature of the liquid at which the flame over the liquid pool becomes self supporting. The heat transfer here you remove the ignition source, the heat transfer from the flame is sufficient to vaporize more fuel to keep the fuel pool burning. Well, let me just add one more point on how low energy solid fuels are ignited like coal or bio mass. These fuels are ignited by sprinkling the small amount of liquid fuel on top of these particles and igniting the liquid fuel.

The liquid fuel, the burning of the liquid fuel transfers heat sufficient heat to the surface of the solid fuel thereby, decomposing it and releasing vapors which can establish gaseous flame around the solid particles and lead to self sustained burning of these particles. What is important to keep in mind is that the volatility of the liquid fuel that is used for ignition, should be such that that there must be sufficient heat transfer from the liquid fuel flame to the surface.

You may have seen videos of tricks where you can dose a dollar bill or a 1000 rupee note bill in ethanol and you can burn it, without burning the note itself or the bill itself. That is simply because ethanol is so, volatile that the vapors go off from the surface and burn sufficiently far away, not transferring enough heat back to the solid fuel or in this case of paper for it to ignite. So, it is important that that the volatility is such that sufficient energy can be transferred back to the surface; so, that the solid fuel starts burning.

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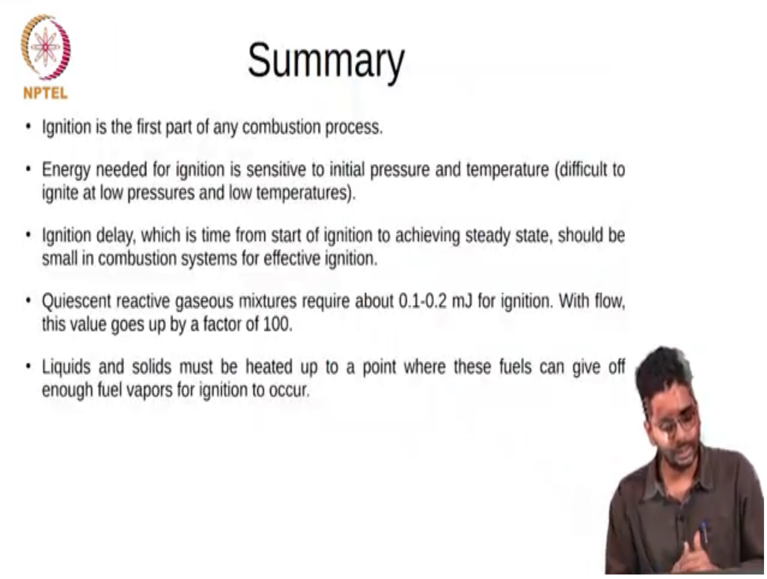

Summary

- Ignition is the first part of any combustion process.
- Energy needed for ignition is sensitive to initial pressure and temperature (difficult to ignite at low pressures and low temperatures).
- Ignition delay, which is time from start of ignition to achieving steady state, should be small in combustion systems for effective ignition.
- Quiescent reactive gaseous mixtures require about 0.1-0.2 mJ for ignition. With flow, this value goes up by a factor of 100.
- Liquids and solids must be heated up to a point where these fuels can give off enough fuel vapors for ignition to occur.

So, in summary we know that ignition is the first part of any combustion process, energy needed for ignition is sensitive to initial pressure, remember 1 over p squared. So, the pressure goes down by a factor of 2, ignition energy goes up by a factor of 4 and temperature. So, remember that it is very difficult to ignite at low pressures and low temperatures. Ignition delay which is a time from start of ignition to achieving close to steady state conditions should be small and combustion systems for effective ignition.

This is a criteria that must be kept in mind while designing the ignition system. Quiescent reactive gaseous mixtures require about 0.1 to 0.2 milli Joules for ignition. This value goes up by orders of magnitude because of the following factors: introduction of a strong air flow and in introducing fuel in the form of liquids instead of gases will increase this by a factor of 1000.

So, the typical ignition energy is required in a gas turbine engine is 1 to 2 Joules, liquids and solids must be heated up to a point where these fuels can give off enough vapors for ignition to occur. As I said this increases the amount of energy required by a couple of orders of magnitude, that is about all that I have to say about flammability limits, quenching and ignition. These are important limit phenomena required for designing of combustion systems ranging from domestic LPG stoves to rocket engines.