Course Name: Theory of Fire Propagation (Fire Dynamics)

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Module 6 – Burning of Solid Fuels

Good morning. So, let us go through some case studies on solid fuel combustion, ok. So, here, these are the case studies we will see today. First one is a thin sheet of paper burning in several angular orientation with respect to the horizontal. Then, when there are multiple sheet kept in parallel vertical sheets kept in parallel how they burn for different separation distances. The third one will be there will be, a say storage of cardboard boxes in a storage facility and if there is a upward flame spread on that how the flame height varies with time. We will see that it is experimental thing. Then the ignition of a matchstick where the energetic portion which actually causes the ignition that is shown here using a high frames per second video. Then we will see the experimental video of flame splitting over a matchstick array, a single area of matchstick kept at some separation distance how the flame spreads, we will see that. Then, for storing, we use a corrugated cardboard one of the sheet of the cardboard, how it burns in a vertical orientation, we will see that.

Finally, we will see the flame downward flame spread on a PMMA slab this thick fuel now. So, this is the first case study, where you can see there is a paper sheet. The paper thickness Tp is about 0.6 mm, which is actually this. So, this is thermally thin, and with respect to the horizontal, this sheet is kept at 90 degrees, that is vertical and 60 degrees and 30 degrees respectively, and you can see the igniter at the bottom, which ignites and the flame actually forms over this and spreads and how the flame spread happens in a thin sheet, concurrent flame spread because gravity is acting at a vertically downward direction and when you ignite this the flame spreads in the direction the buoyancy-driven movement will be vertically upward. So, the flame also spreads in the vertically upward direction in this 90-degree case. So, this is the video which shows that you can see after ignition flame rapidly spreads and we can see the vertices which are formed and since the fuel is thin sheet as the flame spreads the fuel is also consumed and as a gas phase you can see the oscillations because of the entrainment of air. So, this is a basically, 30-centimeter long sheet and the for the flame to consume it are spread over that it takes about 9.2 second the flame spread velocity will be 3.26 centimeter per second. In the left side you show you see the heat release rate with time you can see heat release rate rapidly increases reaches the maximum then as the fuel is consumed it drops rapidly. So, this is the concurrent flame spread on a vertically oriented thin fuel. Now, if the fuel is now kept at 60 degrees angle with respect to the horizontal, you can see the characteristics of the flame spread. Now, you can see that the flame spreads, but in the bottom, there is no much oscillation as you see in the top. The air entrainment in the top portion has lot of oscillation the bottom is a elongated, good flame you can see. So, you can see that the bottom flame is elongated small oscillations are there, but when compared to the top side the oscillations are very less in the bottom. Heat release rate also increases reaches the maximum and drops as we saw in the 90 degree case. Now, when compared to the spread rate at the 90 degree case it took about 9.2 seconds for the 90 degree case here it takes little more time 9.6 seconds. So, the average flame spread velocity is about 3.125 centimeter per second. So, the flame spread slightly decreases. Now, come to the third case where the fuel is kept at 30 degrees oriented with respect to horizontal. Here also the length is 30 centimeter and you can see the behavior here flame spreads gradually you can see the flame will gradually here also the bottom, the flame actually completely spreads, but the oscillations are seen in the top portion as the flame spreads it actually consumes the fuel it takes about 11.1 second to spread to over 30 centimeter thin sheet and consume it. So, the average flame spread velocity decreases now to 2.7 centimeter per second. The heat release rate also is shown here, similar trend is there heat release increases reaches the maximum very fast then, as the fuel is consumed it drops rapidly to 0. So, this is about the effect of angular orientation you can see that the gravity is always in this way upside down. So, you can see that the acceleration see the air entrainment which is actually caused this has two components now perpendicular to the sheet as well as parallel to the sheet. So, in the case of vertical, there was only the parallel component present due to the buoyancy-driven flow. Here, there are two components, this is the cause for the reduction in the flame spread rate, ok.

Now, the second case study is on multiple sheets which are kept parallel to each other vertically oriented. So, here angle is 90 degree with respect to horizontal vertically oriented sheets and we are actually igniting at the bottom. So, the flame is ignited at the bottom you can see that these two sheets basically are kept at a particular separation distance and similarly second and third sheet also in this case there are three sheets. They are kept at a particular separation distance. Now, n equal to 1 corresponds to only one sheet present. So, there is no question of separation distance. So, you can see that the flame spread rate is about 39 mm per second. I have just put the values here for as a function of separation distance, but there is no separation distance for the single sheet case. When you go to n equal to 2, there are two sheets in parallel, ok, the third sheet is not there, but here the separation distance is increased from 5 centimeters 5 mm, 10 mm, 15 mm and 30 mm, ok, this s is in mm ok. So, you can see that as the separation distance increases between these two sheets from 5 mm you record a flame spread rate lower than that in the single sheet case. Then it increases and reaches beyond the value of the single sheet case when the separation distance is about 15 mm, and it almost stays there not increase much from between see 15, 15 to 30 when you double it there is not much variation in the flame spread rate for n equal to 2 case. Now, coming to the n equal to 3, that means, there are three sheets kept and separation distance between any two sheet is the same, which is S it is say 5 mm, 10 mm, 15 mm or 30 mm. So, as seen in the n equal to 2 case you can see that the flame spread velocity is very, very low at low separation distance, and it increases nicely, but again it is below the single sheet case for 10. When you go to 15, it actually exceeds, the both the cases that is single sheet as well as double sheet cases and records the maximum flame spread rate. So, this is the in the graph for the n equal to 3 case, there is three sheets are there burning. And after that, when you increase beyond 15 so to 30 it drops to almost same see you can see this is 40, this is 40 to 44, so not much difference. So, the important point here is based upon the separation distance, the air entrainment in between any two sheets causes the variation in the flame. So, the interaction between the sheets are quite obvious at low separation distances and it the interaction or interference effect vanish vanishes after you have you as you increase the separation distance. So, this is a case done with FDS. You can see clearly that this is the oxygen contours. So, oxygen at the ambient is having a mass fraction of 0.23 and in the flame it decreases. So, it say, one order of magnitude it has decreased. So, this is the flame zone we can say. In the case of two sheets kept at different separation distances, you can see that the low separation distance of 5 mm a case a does not have any oxygen penetration between these two sheets. Only a single flame the gray scale contours where the black shows the highest temperature and white shows the lowest temperature. So, this is the temperature contour, basically. It also shows that a single flame surrounds both the sheets, and both sheets burn as a single entity. When you increase the separation distance to say 10, 15 etcetera slowly you can see that oxygen slightly penetrates in between the gaps and the merged flame comes, that is the flame which is occurring over one of the sheet, is also interfering with the second flame which is formed over the next sheet. But when the separation distance increase, the interaction reduces and at 30 you can see that the interaction completely vanishes. So, both oxygen penetration between the two sheets are clear. Similarly, two almost individual flames form, but here the flame spread rate was slightly higher than the single sheet case because there is some heat interaction between these two flames. So, causing that if you increase the separation beyond, say, 30 mm, there will be no significant effect between the two-sheet case and the single-sheet case. Similarly, for the three-sheet case, now kept at different separation distance of 5 to 30 we can see that even at the three sheets the oxygen contour show that and the temperature contour show that there is no activity between the two any two sheets and a single flame engulfs the three sheets together and burns. When you increase separation distance to say 10 mm and 15 mm we can see that oxygen tries to penetrate, but not much again a merged flame is seen here. But in this case, you can see that the heat interaction from the neighboring or the outer sheets causes a faster propagation of the inner sheet. Going to the largest separation distance of 30 mm we can see that penetration is now good between these two sheets, but even there is some lag between the outer and the inner sheets. So, these are the videos which show that, this is for basically two sheet cases, here, these three, these four and these four are for the three sheet cases at different separation distances. So, this is for the n equal to 2 separation distance of 5 mm we can see that a single flame forms and it consumes the sheet. Now, going to the second case, higher separation distance, a group there is some activity between these two sheets, but obviously, you can see that the, there is a merged flame, that is, interference is still there. Going to the third case, you can see that again a merged flame is seen, but the there is some lag between these two sheets that is the left is seen to propagate at a slightly faster rate than the right. When you increase separation distance to 30 you can see that the flames are almost individually burning in two sheets. Now, going to the three-sheet case at a lower separation distance, it is evident that a single merged flame forms and it actually tries to burn this together. The second case, similar activity is there. We can see that initially the middle sheet try to burn faster, but after that the initial the outer sheets have burnt and the middle sheet burns like a in a slope manner. The third one separation distance is 15 mm here the three sheets again you can see that the merged flame is almost consuming all the three sheets at almost the same rate. Coming to the last case of 30, you can see that due to separation distance is higher individual flames are formed over these sheets, but due to heat interaction between the outer sheets, we can see that there is a faster burning of the middle sheet.

Now, this is the vertical fire spread over a cardboard boxes which are, see these are cardboard boxes which are kept in a storage facility, and there is a big it is very high, basically about 10-meter high storage and if there is a fire at the bottom, ok, some accidental fire how the flame height varies with time is shown here. You can see that the flame is initiated accidentally or wantedly to study how the flame spreads. You can see that initially the flame height is slow and it once the ignition is started radiative heat transfer etcetera occurs you have exponential increase in the flame height is seen both in experiment as well as in the predictions. So, this is how the flame height varies. Concurrent flame initially will be slow, but once it accelerates, it goes at a much, much faster rate and the heat release rate also grows the flame height actually indicates how the heat release rate also will vary, correct? So, the heat release rate also grows in this manner. Now, this shows here 4000 frames per second high-definition video of so, a matchstick. A matchstick you know that at the tip of the matchstick, this is the matchstick. At the tip of the matchstick, normally, you have an energetic material when you rub it with some other material you will have a flame formed and this flame actually ignites the matchstick and the matchstick burns, basically, correct? So, this is the scenario here, but this high-speed video shows how the energy create material which is coated over the matchstick burns, ok. So, this video will play. So, it is now ignited with a heat source, this is a heat source which is brought and very carefully ignited locally ok. It is not ignited by rubbing it, it is carefully ignited slowly at local point. So, the once the ignition has occurred, you can see that ignition occurred at local point, and the the energy material is consumed. You can see the energy material is coated over the surface, correct? Now, as the energy material slowly burning because it is 4000 frames per second video, slowly burning and it is first consuming. Within the time it actually burns. You can see that nothing happens to the wood. The wood here there is nothing even not even blackening of the wood, correct? So, nothing happened, but the wood portion which is coated with this energy material. You can see the char formation. The blackening of this char formation occurs, and slowly, the flame is established. This burns first, then due to this heat, it actually causes volatile material to come out of this and forms a flame over this. So, that is what is this here. It clearly shows that there is a significant time which is required to even ignite the matchstick. So, this primary fuel that is the prime fuel what we coated that is very energetic that actually burns much faster and causes the ignition.

Now, this is the video which has some matchstick array. It is a single array that is single row with matchsticks where the energy material is removed now. The same material as the matchstick, what we can say. Now, this is kept at almost same separation distance that will be some small variation, but it is kept at almost same separation distance and almost same height is protected out of the base, and the first matchstick tip of that is ignited. So, let us see how the flame propagates over this you can see that it is ignited, but the ignition energy is slightly higher, so that two matchsticks are now ignited at the same time. So, we will not worry about the first matchstick now. The second matchstick burns now. The flame does not ignite the third one, but it propagates down slowly, ignites the portions below it, but after it ignites about halfway through the flame spreads over halfway through it ignites the second or the third matchstick, subsequent matchstick, and again, if you see that after spreading about halfway through, the subsequent match is ignited. So, the flame spread initially is slightly faster, ok. Now, you can see that the flame spreads from the third to fourth, fourth now its fifth is ignited, ok. Now, we expect this to continue until the entire array is burnt, correct? So, let us see this. Now, we can see that once this is burnt, you can see that red hot zones where the char itself is now burning and due to the burning the structure actually slightly bends the structure of the thing it is not actually very erect it actually bends and now you can see that the sixth matchstick has ignited the seventh one and it is charring now and after now you can see that after spreading to more than half only it is igniting the next one. Previously, as it comes to about halfway through down it was able to ignite the next one. Now, you can see that after about 80 percent spreading, in one then the next one was ignited. So, that is now lag. So, initially, it was faster. Now, it is slowing down slowly. So, you can see that this height has come now. It has just ignited this. So, that is increasing time delay between the ignition of the neighboring matchstick. So, this is because of several aspects the entrained flow, which is occurring from the sides, ok, etcetera causes this, but please see this, there is no flow of air from left to right or right to left here that is aiding the flow flame spread or opposing the flame spread only the natural entrainment of air occurs. But you can see that now about 90 percent is burned then only the subsequent matchstick is ignited. So, as you go, as a flame spreads over these matchsticks, it is causing more and more delay. Now, you can see that one of the stick, this is, this is heterogeneous wood sticks. So, the burning rate of the wood stick also retards because of some problem in the wood stick itself. So, maybe the moisture content may be high, and so on. So, you can see that it ignites now faster, but after sometime, you will see that it is now spreading at a much slower rate. If you take see the time it has taken to spread over the first 6 sticks. Now, further, some sticks it has taken much more time and now it is in this stick it is not even able to it is slightly pyrolyzing this stick, but not able to ignite this and the flame does not spread after this particular point. So, this clearly shows that this is the wood is very extraneous in nature, and any perturbation in the outside flow may prevent the flame to spread. But please see this this is separation distance where at least the flame has spread halfway through. If the separation distance is slightly increased the flame may not even spread from, say, few few sticks also. But if you can reduce the suppose distance obviously, the flame will spread through the entire length. So, this is about that.

Then coming to this, where see you know the storage box is a cardboard, which is basically corrugated paper. So, it is a thin paper which is having some pores, etcetera. So, this cardboard a single cardboard sheet is taken, and the bottom, you can see there is some prime prime fuel, some small thin layer of liquid fuel. If you ignite this, then this flame will cause ignition of this entire length at one stretch. So, when you ignite it, what happened? Concurrent flame spread we will see. So, ignition is done. So, a flame forms over the entire this. So, this experiment is done in WPI, ok. Most of these experiments what we are reporting here is done in WPI, QSA. So, you can see that the flame is formed, and it ignites this. Initially the flame speed is very low because it has to heat up, pyrolysis gases to come out, then, it basically, sustains a diffusion flame. Now, this cardboard is ignited. You can see that the cardboard is burning here. Char is formed because it is a charring fuel. Again, we see this there is flame has spread, this is the portion. Now, after a flame is initiated due to buoyancy, the flame grows at a faster rate you can see the air out of the zone growing at a much, much faster rate. Now, both the sides are burning you can see the flames from either side then the flame just accelerates. So, you can see that this is very slow initially, but it grows almost exponentially the flame height or heat release rate with time. So, that is the way the concurrent flame spread is happening over the fuel.

So, now, the final case study is on the downward flame spread here. So, for example, this is the PMMA slab, which is very thick basically. So, more than 1 inch thick so, 25 mm thick you can say, and this is the, there are markings we have made here. So, we try to ignite the top portion so, that a flame forms and this is uniformly heated so, that the flame forms in the entire length here and the flame tries to propagate down. So, that is what we are trying to do in this downward flame spread on thick PMMA slab. So, this is actually, thermally also thick. So, when you ignite it so, you understand that ignition is done by a propane torch, carefully, so that the first layer is ignited uniformly, so that it is taken over the entire length slowly. It takes some time to ignite it. You can see that flash one flash is formed, then a sustained flame again is not formed again, now a sustained flame is formed, ok. So, to ensure the complete formation to the entire length, one more coat of layer this heating is done then you can see that the now the flame is formed, and after the removal of the pilot flame also, you can see the first layer has caught up uniformly over the entire length and these two sides here the two sides are covered with aluminum foil so, that the sides will not burn only this portion will burn. So, you can see that initially, the flame is because of thick sheet, it has to heat up the entire solid depth so it is very slow. Yeah, now you can see that, after some time it is now spreading over the, spreading down slowly. So, after some time, we can see the characteristics we want to see here, you can see the bubbling of this. You can see that it melts. The molten layer is actually bubbling over its boiling point so that you can see the formation bubble, and it burns like this. So, this is the characteristic of this flame and the slow, very slow gradually it burns. you can see that the burning forms, and in this case, basically, there is no even though it melts the the molten layer does not drip it actually burns much faster because the boiling point is slightly lower than the melting point in this case basically. So, it burns, right, nicely? The characteristics you can see this is a non-thawing fuel that is there may be some impurities which can cause some impurity layer which can burn, but you can see this. So, when the air entrains here, it is slightly blue in color then after that you can see that the char formation etcetera comes under like a diffusion flame it burns. So, these are the characteristics of the solid fuel burning. So, if you take charring fuel, the char formation is evident. In the case of plastics, etcetera, you can see that the melting and vaporization, etcetera occurs even direct sublimation also can occur in this.

So, these are the case studies which you want to discuss. So, I will stop here.