Flow through Porous Media
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Lecture – 38
Immiscible Flow (Contd.)

I welcome you to this lecture of Flow through Porous Media, we are going to discuss about Immiscible Flow.

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And in this context we have already covered the concepts of saturation, we have already covered concepts of capillary pressure and how capillary pressure depends on saturation, how capillary pressure can be measured. And our next objective would be to define these relative permeability, in terms of this capillary pressure and saturation contact angle, how they relate, how we can define relative permeability and finally, a two phase flow.

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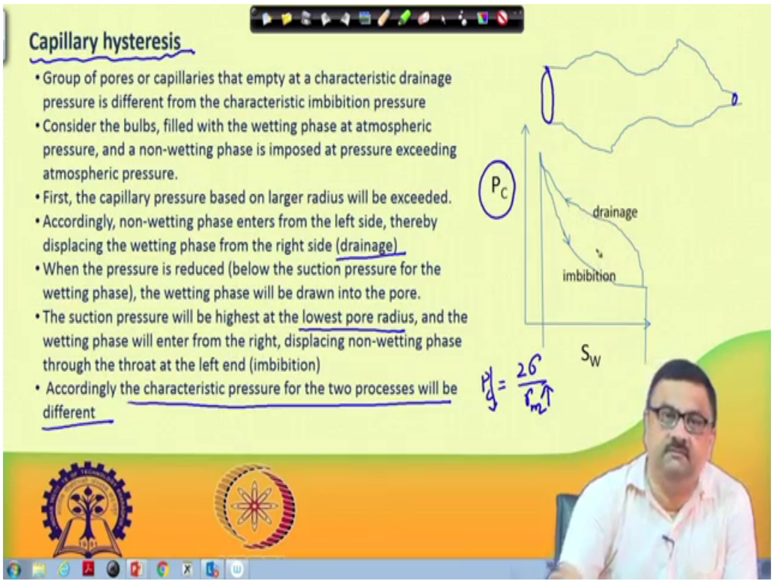

So, what we found earlier was that this capillary pressure P C capillary; pressure P C is a function of saturation and we said that when the non-wetting phase is displaced, non-wetting phase is pushed out of the porous medium by injection of wetting phase that process is known as imbibition, simply because wetting phase is imbibed into the porous system.

On the other hand when it is the reversal; that means, the wetting phase is displaced out so, non-wetting phase is injected which does not happen on it is own, non-wetting phase you have to exhort extra pressure so, that process is known as drainage. So, what I pointed out at that time is that these two curves they do not fall on each other. That means, the pathway; path that is followed capillary pressure versus saturation while going; while on the imbibition route when it goes back it follows the drainage curve which is different.

So, this process is known as capillary hysteresis. So, the reason for this is a group of pores or capillaries that empty at characteristic drainage pressure is different from characteristic imbibition pressure. you recall you must recall that when we said that there is a pore something like this. For example, consider the bulbs filled with wetting phase at atmospheric pressure, let us say we are looking at this particular pore. Here this is filled with wetting phase and now you want to inject non-wetting phase into this pore.

So, consider these bulbs, filled with wetting phase add atmospheric pressure and non-wetting phases imposed at pressure exceeding atmospheric pressure. So, if one wants non-wetting phase to be introduced into this pore one has to have the pressure higher than atmospheric pressure and that difference is the capillary pressure we all are aware of it and this capillary pressure is inversely proportional to this radius of curvature here. So, it is so, first the capillary pressure based on larger radius will be exceeded, we remember that capillary pressure is given by 2 sigma by r m..

So, in this case; I mean, the radius when the radius is large capillary pressure is small. So, as one x increases the pressure above atmospheric, the first the capillary pressure for the larger pores will be exceeded. So, non-wetting phase will enter into those pores where the pore throat is larger. So, larger pressure radius will be exceeded accordingly non - wetting phase enters from the left side. So, if we look at this particular pore this one is a this pore throat is larger, these pore throat is smaller. So, we expect that the non-wetting phase enters from the left side, there by displacing wetting phase from the right side so, this process is known as drainage.

On the other hand when the pressure is reduced; so, our side pressure is reduced below the suction pressure for the wetting phase the wetting phase will be drawn into the pore. So, wetting phase will be then in that case drawn into the pore and at that time they have this advantage of capillary pressure. In this case capillary pressure goes against; it against the flow of oil into the pore flow of non-wetting phase into the pore whereas, when it comes to flow of wetting phase into the pore it has a advantage, is it like we have in capillary rise we have there is a suction effect.

So, the suction pressure will be highest at the lowest pore radius, because suction pressure once again depends on it is proportional to 1 by r m. So, naturally suction pressure would be higher when the radius is lowest and a wetting phase will enter from the right. So, in this case the first wetting phase will enter from the right not from the left, because here the; that suction would be more. So, displacing the non-wetting phase through the throat at the left end so, the non-wetting phase will be displaced from the throat at the lift end.

So, accordingly you can see the drainage process; that means, when non-wetting phase enter into the pore displacing the wetting phase that happens in this direction whereas, when wetting phase enters that happens from the other direction. So, you can; one cannot expect that they will fall on the single fall on the same line, because it is not just displacement of one phase by the other in the same direction. So, because of these so, one can see that these characteristic pressure for the two processes will be different so that is why you we expect a capillary hysteresis these two curves they may not; they will not fall on each other.

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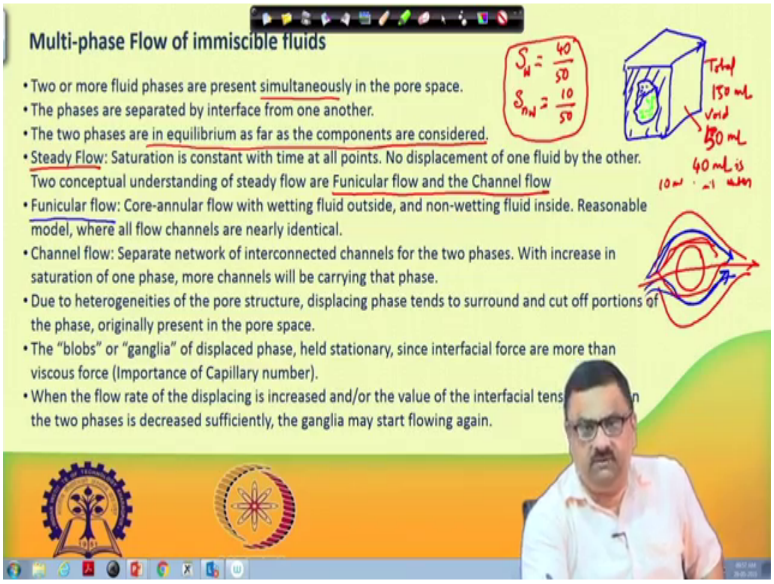

So, now we start thinking about this multi phase flow of immiscible fluids. So, when we have multi phase flow of immiscible fluids what all we have in mind here, first of all what we see I mean let us see what kind of model we have in mind. I mean when we have I have a pore space we said last time right, we have constructed a pore space, let us say we picked up a volume element here and we should let us say we have this as a pore space. So, this is all solid so, this is the pore space and these pore space we said is occupied by two different phases; one phase is wetting phase, the other phase is non-wetting phase. So, one is given by blue, another is by green. So, how we conceptualize this flow of two phases happening together in a porous medium.

So, first of all what we assume here is that, the two or more fluid phases are present simultaneously in the pore space. So, they are the every grid in the pore space if I break it down into 100 or 1000 grids and every grid some saturation is assigned so; that means, at every grid a part of the void volume is occupied by wetting phase part is non-wetting phase ok. It differ a two phase system, for a three phase system you can have three phases for example, if you have if one has oil, water and gas so, it would be a three phase system. So, all three would be present in fact, there are n number of phases all n phases are present at that particular grid. So, they are present simultaneously in the pore space. The phases are separated by interface from one another that is what the phases, phase means water and oil and there is an interface they do not mix.

So, the two phases are in equilibrium as far as the components are concerned that is also another very important issue, we have let us say two phases and each phase has some dissolved solids ok. So, let us say I have one organic phase and one aqueous phase, now I have some salt which is present in the aqueous phase and the same salt is also present in the organic phase. So, then there will be a partition of that salt between the aqueous phase and the organic phase and this partition there is something called a distribution coefficient. Distribution coefficient we generally denote it by k, that distribution coefficient is the you would probably put it as mole fraction or mass fraction of component I in one phase divided by mole fraction or mass fraction of that same component in the other phase.

So, if there are two phases, one can have a distribution coefficient something like this. So, this is an equilibrium value; that means, I bring in two phases, one phase has some salt other phase has does not have a salt. But then we shake it well and then let it rest I expect there would be sufficient interface area through which the salt can move from one phase to the other and an equilibrium is reached. And at equilibrium the salt concentration of in say aqueous phase and the salt concentration in organic phase they are ratio; these two concentration ratio they would be following some distribution coefficient ok. So, this is at equilibrium, if the equilibrium is not reached this may not be satisfied.

So, equilibrium means they have to be brought in to the two phases have to be brought in intimate contact with each other so, that the solute transfer from one phase to other can take place and then you have to give it sufficient residence time. So, that you have to allow them to reach equilibrium, and after it reaches equilibrium if you find out what is the concentration of that salt in the aqueous phase and the concentration of that salt in the organic phase and their ratio. So, they will find that it follows certain equilibrium value which can be determined from thermodynamic considerations or not. So, we are assuming the two phases are in equilibrium as far as the components, components means they dissolved solute; dissolved salt so, as far as the components are considered.

Now in this context there is something called a steady flow, steady flow I briefly talked about a steady flow in the last lecture. This is something like these that if let us say I have these; I have say let us say wetting and non-wetting phase, water is a wetting phase, oil is a non-wetting phase and they are coexisting in this let us say in the ratio of; let us say this total volume is I call it let us say 100 let us say total volume is 50 ml out of that we said 40 ml is; 50 ml is the total. Let us put it this way total volume is let us say total volume is 150 ml total volume, total is 150 ml; out of 150 ml then we have let us say porosity is one-third; that means, 0.333.

So, then in that case we can expect the void volume is 50 ml, and out of this 50 ml; let us say out of this 50 ml, 40 ml is water and 10 m l is oil, let us say 40 ml is water and 10 ml is oil. So, that is how it splits 40 plus 10, 50 and 50 one-third of 150 is 50 so, porosity is one-third. So, now, in this case let us say we are having a flow through this system. So, in this case if somebody calculates the saturation, the saturation of water would be in this case 40 divided by 50 and saturation of non-wetting phase that would be; saturation of wetting phase is 40 divided by 50 and non-wetting phase would be 10 divided by 50 so, that is how the saturations are defined for this particular grid.

Now let us say I am establishing a flow through the system whereby first of all this entire porous medium is following this. So, at every grid this is what is followed and then when I am injecting let us say what is their ratio, I think the ratio comes to 4 is to 1 right. So, suppose I inject the volume of water and volume of oil I put them together and mix and send it. Obviously, I cannot mix them, but I can disperse the two phases; disperse means generally if I have two phases you will find one would be the continuous phase; that means, there is a maze here and in that you will find other phase would be generally present in droplets. I mean if you take water and oil in a test tube and shake it and you will see that this is what would be formed. I mean there would be small droplet us of one phase embedded in as if a matrix of the other phase. So, let us say we can create this kind of a two phase system.

So, let us say we create this kind of two phase system by mixing which has 4 is to 1 ratio of water and oil and involve by volume and then we inject this through the system. Then

I can expect that the saturation will not change because the saturation it is the same ratio the oil wetting and non - wetting phase they are flowing so, we do not expect them to change at this grid so, that is referred as a steady flow. So, what it says is saturation is constant with time at all points no displacement of one fluid by the other so, this is a condition of steady flow.

So, what is unsteady flow, suppose it is filled you have this kind of a system with water and oil in this ratio and then you start injecting oil. So, then in that case you will find oil will enter into some of the space that was originally occupied by water. So, the saturation at different grades they will change so, then we call it unsteady flow, because saturation add different grades they are changing with time.

So, now, when it comes to these saturates; when it comes to the steady flow one can think of two conceptual model of steady flow; one is called funicular flow, another is called channel flow. What is funicular flow, think of this I mean this concept of funicular flow we already talked about we mentioned that pore may look like this. So, then we can see that the oil would be occupied at the center and water would be flowing through the side.

So, then it is; so of this funicular flow if you look at the definition of funicular flow core annular flow; that means, when oil and water both are flowing through this pore, you see water is flowing through the annulus or the wetting phase is flowing through the annulus whereas, the non-wetting phase is flowing through the core the center of the pore. So that means, funicular flow says core annular flow with wetting fluid outside I see blue color outside and non-wetting fluid inside, this is a very reasonable model when all flow channels are nearly identical.

This is the way the flow will take place and one can see that if the one if you continuously start injecting oil, then you will find on an instead of water, no water only a oil. Then you will see that this part grows these part grows gradually, but there would be some oil would be trapped some water some wetting phase would be trapped on the wall which you can never remove. On the other end when you are injecting water alone there will be some oil trapped at the center which cannot be removed. I mean it can be removed only when if you can reduce the surface tension or if you can impose a very high pressure maybe you increase the viscosity of the fluid that is flowing in. So, you have to just by simple water and water and oil or wetting and non-wetting phase there would be some remnants which is called a residual saturation so, this is what is funicular flow.

So, it is expected that the flow channels are nearly identical, there is an alternative concept which is called channel flow where 1 x; this is proposed that separate network of interconnected channels. Separate network of interconnected channels for the two phases, with increase in saturation of one phase more channels will be carrying that phase. So that means, what it says is that one may have the some channels which are totally dedicated to wetting phase and some channels which are totally dedicated to non-wetting phase. And intuitively we can see that the channels the pores which are larger; obviously, non-wetting phase tend to follow those channels whereas, the channels comprising a pores which are smaller wetting phase who tend to flow through them.

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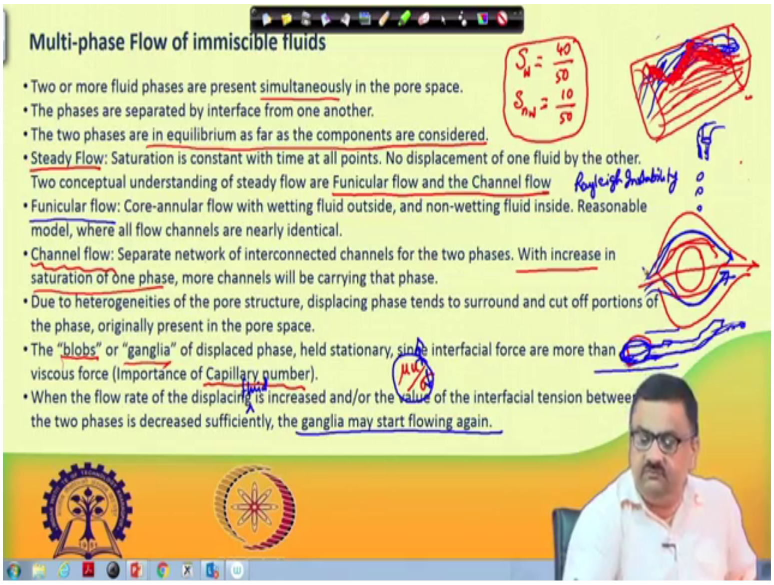

So, this separate network of interconnected channels for the two phase; that means, if this is the porous medium so, you have a channel which is probably forming this part of the channel; this part of the porous medium you see only wetting phase is flowing. Whereas, you see the other part is you get only the non-wetting phase is flowing. Now as you increase the saturation of one phase with increase in saturation of one phase more channels will be carrying that phase so; that means, when you increase the oil phase saturation; that means, instead of water you are injecting only oil that is only non-wetting phase, you will find that some part of the channel which was originally was taken used by water now the oil will infiltrate into those and those channels will be used for oil flow.

In fact, if you continue to increase this way then at one point you will find that oil is flowing almost through most of the parts only thing is it is leaving some portions here. For example, some water remains trapped so, this part. So, this is giving rise to what you call the interstitial saturation or the, on the other side if you inject water. So, then water would be flowing through the channels which was earlier occupied by oil, and then at some point it will cut off a portion of the channel and oil will be sitting there as a blob. So, that is resulting into so, called residual saturation.

So, essentially it is this is what I am writing here is separate network of interconnected channels for the two phases with increase in saturation one phase more channels will be carrying that phase. So, due to heterogeneities of the pore structure displacing phase tends to surround and cut off portions of the phase originally present in the pore space, just like here they have cut off the blue phase. So, blue phase gets stranded and here it is the non - wetting phase here also it is using this pathway for non-wetting phase so, here it got trapped this water so, borrow wetting phase here.

So, the “blobs” or “ganglia” so, these are the words used for this kind of cutoff phase, the blobs or ganglia of displaced phase held stationary since interracial forces are more than viscous force. So, in this case this remains stationary because it is I think in this context one must note what is this capillary number, there is a dimensionless number just like we had a Reynolds number this capillary number is given by mu u divided by sigma.

So, when the viscous force is higher capillary number would be higher whereas, when surface tension is higher capillary number would be lower. So, the when the interfacial forces are more compared to viscous force, then these blobs or ganglia will remain stationary. So, there would be threshold capillary number at which this blob or ganglia will remain stationary.

So, one thing one can do at this time is they can reduce this sigma; so, that the capillary. So, how do you reduce a sigma, use a surfactant. So, by reducing this sigma one can, but; that means, that the interfacial tension is reduced so, this capillary number would be higher so; that means, the domination of viscous force over interfacial force happens. So, at that time one can expect the blob to again start moving.

See basically the implication of this capillary number is let us say I have a blob here and I am submitting this blob to a viscous domination. So, what that means, is that viscous effect essentially it means that this there is a layer and then next layer having a high this here the velocity is 0 here, the velocity is more here, the velocity is even more here, the velocity is even more. So, these particular blob would be stretched if you impose viscous force then; that means, this particular blob will be stretched. This particular blob will take a shape like this when it is stretched by the viscous force because you are sliding one layer against the other is shearing this blob so, this should be taking a shape like this.

On the other hand the interfacial force will try to retain it as it is, as it will we try to retain it as a sphere. So, when the viscous effect does not dominate when surface tension effect dominates so, it will remain there as a as it is. Whereas, when viscous effect dominates this will be stretched in the form of layers this would be stretched and then this would be forming smaller probably if it breaks down; I mean, anything if someone stretches. I mean it undergoes a process known as Rayleigh instability, you cannot continue to holds a string something in this way. You may see this kind of a similar effect when somebody works with a dripping faucet problem, a string of fluid comes from a tap and then that breaks down into spheres. So, this is known as dripping faucet problem and this happens because of some instability which is given the name Rayleigh instability.

So, here also the same thing that you this blob will be stretched into a string and then it would be broken down into smaller blobs and then it would be carried downstream. On the other hand if the surface tension is stronger it will retain it is integrity and it will remain as it is. So, this there would be a threshold capillary number on which when this ganglia would be held up or this ganglia will be moving, ganglia is breaking down into further smaller droplets. So, these are and this threshold capillary number one can change the capillary number of the; one can change the operating capillary number; obviously, by playing with these parameters. For example, one I mentioned just now if somebody can reduce this interfacial tension by adding surfactant ok, so these are some of the ways to do these here.

So, when the flow rate of the displacing; when the flow rate of the displacing fluid is increased and or the value of the interfacial tension between the two phases is decreased sufficiently. So, when the velocity is increased this u is increased or sigma is decreased. So, interfacial tension is decrease sufficiently that ganglia may start flowing again. So, this is something which is important. So, when the velocity is increased; when the velocity is velocity is increased means that you are putting more the domination of the viscous force, and interfacial tension is decreased means the surface tension force becomes less significant.

So, when this happens the capillary; in operating capillary number will increase and at that time one can expect that the ganglia will start flowing again. So, essentially you can see this is how the; this is how these flow of two phases they are conceptualized. I mean whether we go by the funicular flow or whether you go by the channel flow at the center there will be a; whether you go by the funicular flow or whether you go by the channel flow there would be some kind of blob or ganglia. So, this blob could be at the center of the pore or blob could be a trapped phase here as we pointed out. So, either of it would be a blob or ganglia inside a porous medium which is cut from the string of flow. So, if you have a flow string now the flow string is cut and a blob has formed.

So, this blob and because of these we have interstitial saturation or residual saturation in the two sides. So, now, this blob can be you can make this blob to move; obviously, one way is to change the saturation I mean, if you have; if you see the water is getting water is maintaining a blob as a cut off phase and because you are injecting oil. So, now, you instead of oil you inject water then again you see this a channel will be established. So, a water channel will form with the blob on the pathway and so, you will have flow of water through that space. But instead of that if you really want to take this out want to take this blob or ganglia that is held up if really if somebody wants to do that then one has to play with the capillary number, particularly they have to increase the velocity and they have to decrease the surface tension, they have to decrease the interfacial tension.

So, these are some of the ways to make those blob or ganglia that was held stationary to have them moving again ok. So, this is the overall model that we have in mind when we go for two phase flow or multi phase flow in here. So, this is all I have as far as this module of lecture is concerned I will continue this exercise of two phase flow in the next lecture.

Thank you very much.