Heat Transfer And Combustion in Multiphase Systems

Prof. Saptarshi Basu
Department of Mechanical Engineering
Indian Institute of Science-Bangalore

Lecture 15
Transport processes at interface with key concepts-I

So, last class we; before we go on to the wetting how droplet actually wets and what is the role of contact angle. Last class we said that surface tension actually is a function of temperature and the individual mole fractions of the individual components that are present. So, last class we wrote that this class let us just finish this.

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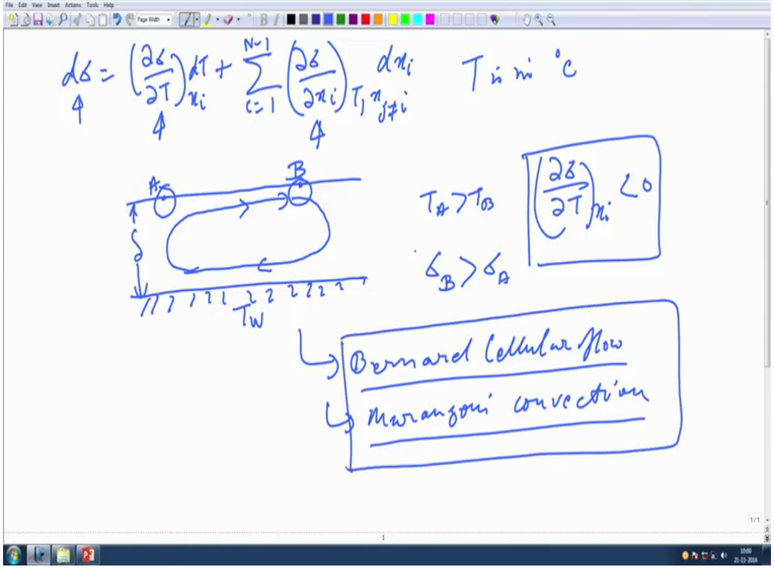

$$d\sigma = \left(\frac{\partial\sigma}{\partial T}\right)_{x_i} dT + \sum_{i=1}^{N-1} \left(\frac{\partial\sigma}{\partial x_i}\right)_{T, x_{j\neq i}} dx_i$$

T in °C

$T_A > T_B$

$\sigma_B > \sigma_A$

$$\boxed{\left(\frac{\partial\sigma}{\partial T}\right)_{x_i} < 0}$$

Bernard Cellular flow

Marangoni convection

So, this is a variation with respect to temperature and then consequently these are the different mole fractions of the different species that are present. The surface tension how does it vary with constant T okay, now in this particular case we show that the change in surface tension is actually linked to the temperature and the individual variations with respect to the mole fraction of the individual components that are present in the fluid okay.

Now and in here the temperature is in degree Celsius okay. Now how is this useful in any practical applications, now let us assume that you have a surface and this is a very common occurrence at a temperature of Tw. There is a liquid layer that is sitting on the top of this heated surface okay. And this layer has got a thickness of about delta okay.

Let us not be bothered about what will be the magnitude of delta. Now at two points on the surface let us take a point A and a point B okay. Now in this point A and B what we can see is that temperature at point A is actually more than the temperature at point B okay the temperature at point A is more than the temperature at point B okay.

So, naturally what will happen is that the surface tension magnitude at point A and point B will be different. Now since surface tension is normally decreases with increase in temperature that means if TA is greater than TB then the surface tension at B okay will be actually greater than the surface tension at A.

So, naturally what will happen is that the flow will be dragged from the area of low surface tension to the area of high surface tension and will lead to our re-circulating flow like this okay. So, understood so, because this gradient is negative it implies the surface tension normally decreases with increasing temperature.

So, since B is at a lower temperature than A therefore its surface tension value is higher than A. So, naturally the fluid near the interface is pulled towards B from a low surface from a high surface tension to a low surface tension region okay pull towards the region with higher surface tension. So, the higher surface tension region basically pulls okay.

As a result of that you create this re-circulating flow and this flow is called the Bernard Cellular Flow okay. So, this is called a Bernard Cellular Flow this happens when a horizontal pool of liquid, is very thin layer of liquid is actually heated from the bottom okay and this flow is basically called the Marangoni convection.

We will cover more about this Marangoni convection in later when we actually watch it with respect to droplets. But this is basically what is called the Marangoni effect that is a motion of the liquid is caused due to a gradient in surface tension because there is a spatial gradient in surface tension which is created due to a spatial gradient in temperature or a spatial gradient in the individual components.

We get a re-circulating flow in this way in this case it is re-circulating flow and it is called basically the Marangoni convection okay. Similar things can happen in other types of mediums as well in other types of configurations as well okay. But in general this is what the surface tension driven flow is all about okay.
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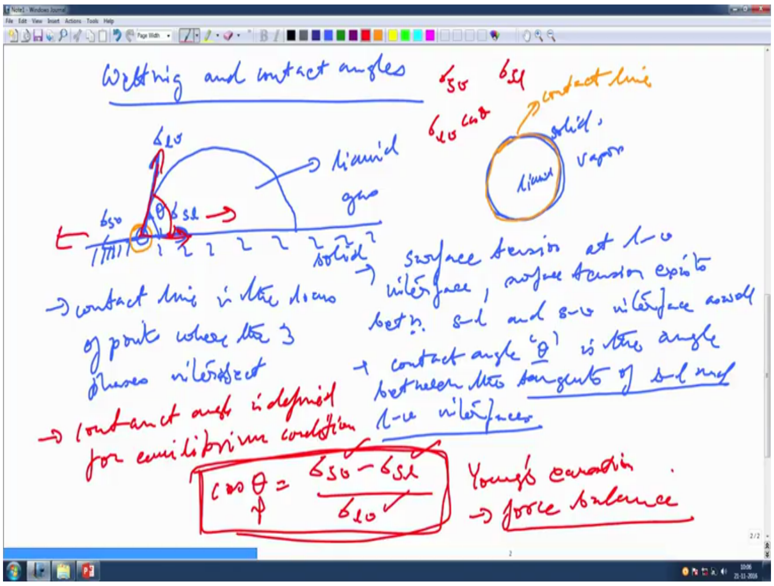

Wetting and contact angles

→ contact line is the locus of points where the 3 phases intersect

→ surface tension at l-v interface, surface tension exists betn. s-l and s-v interface as well

→ contact angle 'θ' is the angle between the tangents of s-l and l-v interfaces

→ contact angle is defined for equilibrium condition

$$\boxed{\cos\theta = \frac{\sigma_{sv}-\sigma_{sl}}{\sigma_{lv}}}$$

Young's equation

→ force balance

Now let us look at, now the wetting and the contact angle behaviour, coming to the topic and here also we will find later on that Marangoni flow will be an important aspect. So, wetting and contact angles okay, now wetting and contact angle let us assume that there is a surface, whatever that surface may be okay.

And there is a droplet which is basically sitting on that substrate okay. Now this is there is a liquid this is a liquid medium, this is a gas, this is a solid okay. So, the sub stress, so the droplet actually sit on this particular substrate okay. And as you can see that there is a point or if you; if this is the side view from the top view it will be like a circle, right.

So, there is a circumference around which okay there is a three phase contact line that means there is a liquid, there is a vapour and there is a solid okay all at the same region. Now this particular substrate let us look at it, there are three surface tensions which are acting on it okay. One is called Sigma Lv, one is called Sigma Sl and the other one is called Sigma Sv.

Now the angle that it makes over here is called theta. So, theta is basically the angle that this droplet makes with this substrate okay. We will talk about these things a little later so in addition to the surface tension at lv interface okay. There is, there are surface tensions that exist surface tension exists okay between sl and sv interface as well okay.

Now the contact angle the contact angle theta okay is the angle between the tangent of sl and lv interfaces okay. So, there is an lv interface okay and there is a sl interface. So, the angle if you draw the tangent of course with a solid surface the tangent is nothing but the horizontal line.

The lv interface it is at that particular point if you look at that particular point it is the tangent that it makes okay. If you draw tangent to the liquid surface that is basically the angle, so this is the contact angle is the angle between the tangent of the sl and the lv interfaces okay. So, the contact line is basically, contact line is the locus of points basically locus of points where the three phases intersect.

That means as you can see that if you highlight this particular point, this is the point or this is the circumferential region okay. Because what you look at the point in the side view is basically as the circumferential parameter type of line. This is nothing but the contact line okay.

So, the contact line is basically that okay. So, the contact line is defined only for equilibrium positions, contact line, the contact angle is defined for equilibrium condition okay. So, the equilibrium condition means that the droplet is at a static condition, it is not moving okay and that relationship is given by cos theta where theta is the angle be made by the tangent, this and this okay.

Sigma sv - Sigma sl divided by Sigma lv okay. So, this is basically called the Young's equation okay. So, it is basically nothing but a force balance in the horizontal direction. So, if you look at this particular expression okay what does it actually tell you when it is an equilibrium condition okay.

So, this is basically Sigma sv okay and then it is Sigma sl, so these are these points towards the two directions the positive and the negative axis. This is basically decomposed in this direction, so that this will be nothing but sigma lv cos theta okay. And then if you do the math this has to be equal to this because all of them are acting on the perimeter okay.

So, all of that thing cancels out okay and therefore you get this particular relationship from the Young's equation okay. So, let us look at you look at this thing in a little bit more details it is basically nothing but a force balance. So, Young's equation is nothing but a force balance which gives a relationship between the contact angle which is theta.

And the corresponding surface tension values the solid vapour solid liquid and the liquid vapour interfaces, okay.
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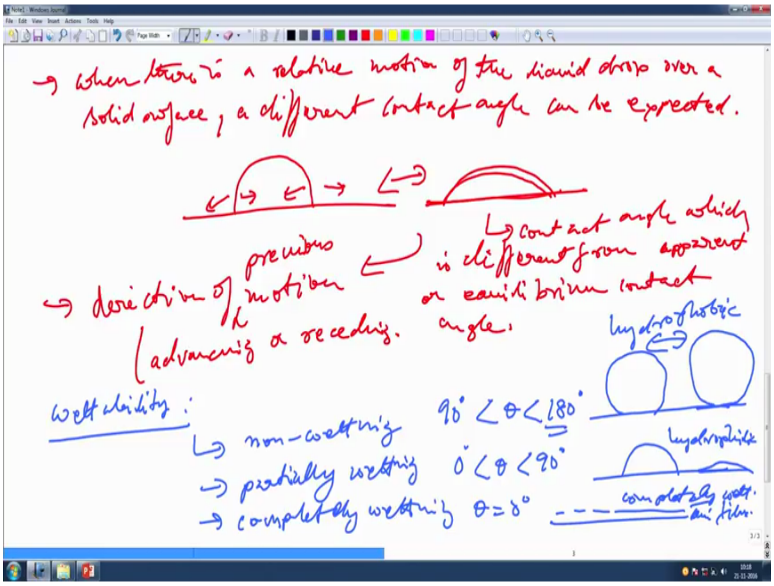

→ when there is a relative motion of the liquid drop over a solid surface, a different contact angle can be expected.

↳ contact angle which is different from apparent or equilibrium contact angle.

→ direction of previous motion (advancing or receding.

Wettability:

↳ non-wetting $90^\circ < \theta < 180^\circ$

→ partially wetting $0^\circ < \theta < 90^\circ$

→ completely wetting $\theta = 0^\circ$

Now let us look at this thing in a little bit more details okay. Now this is valid only when you taste in a equilibrium condition. Now let us look at when there is a relative motion of the liquid drop over a solid surface. When there is a relative motion of the liquid drop over the solid surface a different contact angle can be expected okay.

When the relative motion stops, so when there is a relative motion of the liquid drop that means there is as you know the surface is there now as you deploy the droplet it actually spreads or it actually contract, right. Whatever may be the situation, so, there is a relative motion of the drop over this solid surface okay.

At that point of time a different contact angle is expected almost at every time instant right when it is actually spreading or it is actually contracting. When the relative motion actually stops okay so after this at some point it will assume they are shape like this. So, this is the point where the relative motion has actually stopped.

Here it will show an apparent contact angle or a contact angle rather let us not put it as apparent, a contact angle which is different from the apparent or equilibrium contact angle okay. So, when there is a relative motion between the two surfaces when there is a relative motion between the drop and the surfaces.

There is a contact angle is different at each time instant and when this relative motion stops this contact angle is different from the equilibrium contact angle that we defined earlier okay. So, it also depends this contact angle also depends on the direction of motion of the droplet that means whether it is spreading whether it is contracting.

The direction of the previous motion this angle depends on the direction of the previous motion that means whether it is advancing or receding okay.

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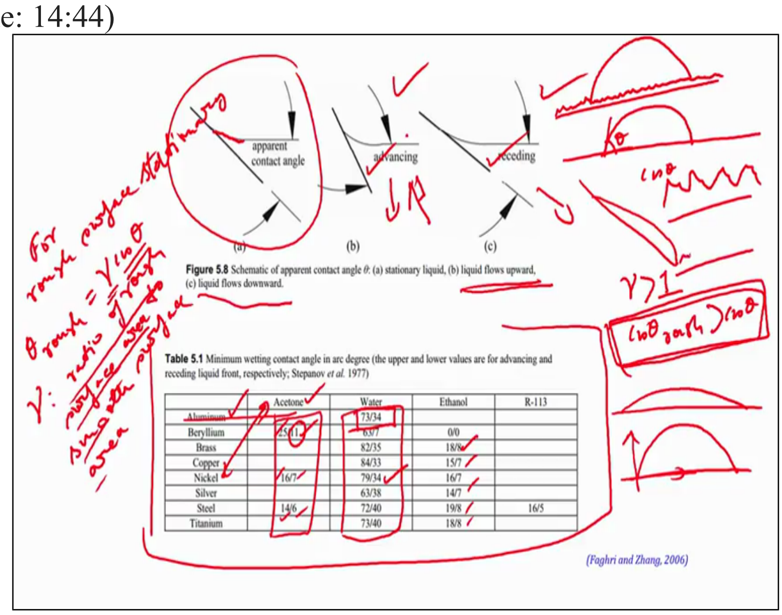

Figure 5.8 Schematic of apparent contact angle θ: (a) stationary liquid, (b) liquid flows upward, (c) liquid flows downward.

Table 5.1 Minimum wetting contact angle in arc degree (the upper and lower values are for advancing and receding liquid front, respectively; Stepanov *et al.* 1977)

	Acetone	Water	Ethanol	R-113
Aluminum		73/34		
Beryllium	25/11	63/7	0/0	
Brass		82/35	18/8	
Copper		84/33	15/7	
Nickel	16/7	79/34	16/7	
Silver		63/38	14/7	
Steel	14/6	72/40	19/8	16/5
Titanium		73/40	18/8	

(Faghri and Zhang, 2006)

Now let us look at the presentation. So that we can get an idea that we have okay. Now the business for example a pictorial diagram in which we show that what are; this is the apparent contact angle. So, you can see that this is what the droplet actually makes okay. This is for a stationary liquid the first one okay.

So, that is the apparent contact angle that you mean let us not be bothered about those things that you see okay. This is the apparent contact angle that it actually makes. Now in some cases say for example if the liquid flows upwards okay then you get what we call an advancing contact angle okay.

And in the other case when the liquid flows downwards okay this is upwards okay you get a receding contact angle. So, that means here the droplet is kind of its contact angle is actually decreasing or increasing rather. In the case of receding it is actually getting more and more like a flattened pancake type of a form okay.

So, this is what the liquid flows downwards, this is what happens when the liquid flows upwards, this is the advancing contact angle, this is a receding contact angle okay. Now that is important because this is the direction of motion this is the static and stationary shape. These are the two possible motions that you can get.

So, you can get both advancing as well as both receding contact angle okay and we will show some of the cases they for example this table 5.1 if you look at it okay say the two are substrate is aluminium the liquid is acetone okay. So, here you can see the upper and the lower values okay.

That is 25 is the upper value 11 is the lower value in the degree for advancing and receding. So, advancing liquid with advancing acetone drop will exhibit a contact angle of about 25 degree Celsius and the receding drop will exhibit a contact angle of about 11 okay. In the case of water this difference is this is verillium with acetone.

In a case of aluminium with water you can see that there is a quite a bit of a difference in the advancing and receding contact angles. Similarly there are values given for acetone nickel combination okay. These are the two these are very low values of the contact angle that means it would translate to a very thin liquid layer okay or a liquid cap like this okay.

For water however when you actually have a situation like this, this is more bulgy. But it is still not 90 degrees; it is below 90 degrees okay. So that is why it is like this okay. So, similarly here we can see for ethanol of course because of the lower surface tension all these values are a bit lower on the lower side okay.

So, ethanol and water because of the high surface tension values exhibit a higher contact angle acetone is also not very high surface tension so all these things actually shows the two ranges of values advancing will be obviously higher because the liquid is actually contracting like this okay.

And receding will be obviously lower okay because the liquid is actually spreading. The previous motion is actually spreading okay. So, these are the two types of motions that you will normally expect to see in these cases okay. Now however for rough surfaces if the surface is rough okay.

For rough surfaces the contact angle that is exhibited by the rough surface is given by basically gamma cos theta. Now gamma cos theta where gamma is basically the ratio of rough surface area to smooth surface area, got it, so, if you have a surface which is given like this is not a smooth surface right.

Now if you take another surface of similar kind but you have all these roughness’s which are in green on the top, right, okay. So, your contact angle in this case versus the contact angle in this case would be different okay. In fact the contact angles for this particular case will be a function of gamma into cos theta.

So, cos theta is the contact angle for this, this is your cos theta okay, this gamma cos theta gamma is the ratio of the rough surface area to the smooth surface area. So, obviously one can see that gamma will be greater than 1 right for rough surfaces it has to be. By definition the gamma will be more than one.

So, naturally the cos theta rough okay will be greater than your cos theta okay. So, cos theta rough will be greater than cos theta which would imply that the rough surface the cos component of the contact angle is always more than what you expect on a smooth surface right.

So, this is one of the key relation of course the substrate are still the same you cannot compare the roughness across two different substrate. It is the same substrate, say for example you take aluminium and you have a very smooth finish where the rms roughness is very, very low.

On the other hand you have another substrate in which the roughness values are very high. So, therefore there is a lot of as I showed roughness is like this right okay and in other case the roughness is like that so naturally this is more rough than this. And when you place a droplet on this obviously the contact angle on this will be different than the contact angle over here.

So, moving on let us look at the journal entry okay. So, now we know that what the contact angles are. Now let us we are in a perfect situation now to define something called wettability. Now that you know what an advancing and the receding contact angles are okay. So, when we define wettability non wetting, we define categories non wetting surfaces are where the contact angle is falls in this range.

That means the contact angle is greater than 90 degree but less than 180 degrees I can draw this will be more or less like this and it can go up to like this, so it is called hydrophobic surfaces essentially. So, for example if you put wax on a surface and you put a droplet on the top of that you will find that it almost sits like a like a sphere, almost completely like a sphere.

That means the contact angle is very high close to 180 degrees okay. Partially wetting contact angle will be 0 greater than theta less than 90 degrees okay. So, that means this particular thing exhibits anywhere between this to this okay and completely wetting would imply theta is equal to zero degrees that means it is a film, flat film okay.

So, this is more like hydrophobic we will check what hydrophobic are. This is more like hydrophilic and this is completely wetting this is a thin film, completely wetting thin film. And thin film we will do in a lot of details later on okay.

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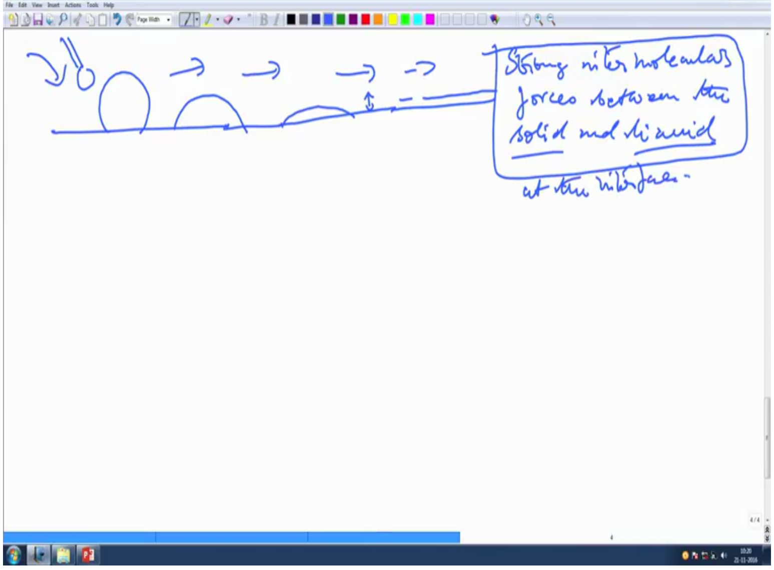

Strong intermolecular forces between the solid and liquid at the interface.

So, this actually gives you the first idea that definition of wetting, okay, now if you imagine bringing a small amount of liquid with an initially dry solid surface, okay liquid in there are several possibilities the liquid may not wait the surface it might actually form these droplets. And these droplets actually sit’s on the substrate.

On the other case the liquid may actually completely weight the surface and form a film. So, there are two possibilities that can actually happen okay. So, what is wetability dependent on like in some cases it spreads in some cases it forms this nice sphere’s okay. So, what determines, so you have a substrate and in which you try to deploy a liquid okay.

So, you bring basically a pipette or a syringe like this okay and it can form something like this it can form something like that. It can form something like this or it might actually completely wet the surface. So, what determines this to this, this to this and this to this okay. So, wetability is attributed to the strong intermolecular force near the sub interface between the solid and the liquid.

So, it is basically nothing but the strong intermolecular forces between the solid and liquid right, forces between the solid and the liquid at the interface okay. So, that is the most important criteria will cover it a little bit more details later. But it is basically their nature of interaction between the substrate and the liquid.

So, it is dependent on both the substrate as well as the liquid, so they are like pairs okay. And that is what determines that whether a droplet will sit nicely or it will spread. So, it is highly dependent on the surface properties and as a result of that the intermolecular interactions between the solid and the liquid at the interface okay.

So, we will stop at this particular lecture over here in the next lecture we will speak on the spreading and the disjoining pressure okay thanks.