Chemical Process Safety
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Lecture 19
Source Model for Pool Boiling

So, welcome to this model of source model for Gases. In this, before we start this module, let us have a look that what we have studied in previous modules.

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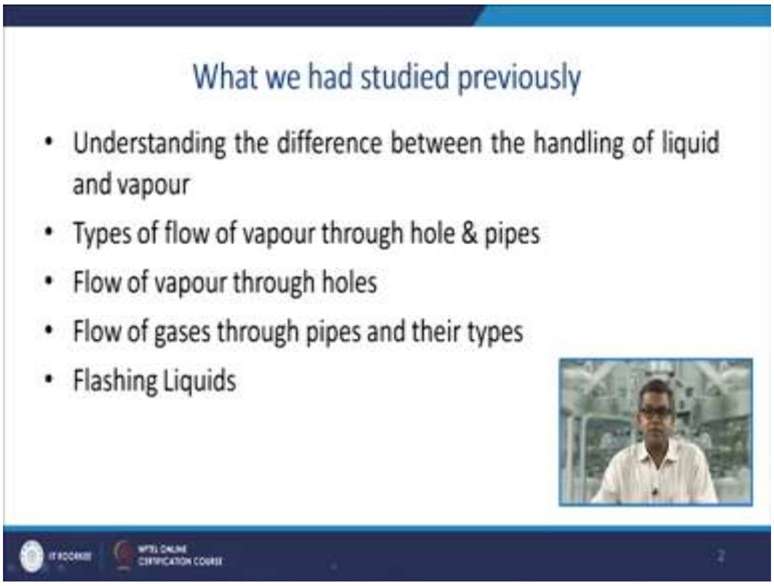

We have gone through the difference between the handling of liquid and vapours. We have discussed various types of flow of vapour through hole and pipe and the model and we discuss the various models. Flow of vapours through holes we have discussed about a flow of gases through pipes and their types. We have gone through the flashing of liquids.

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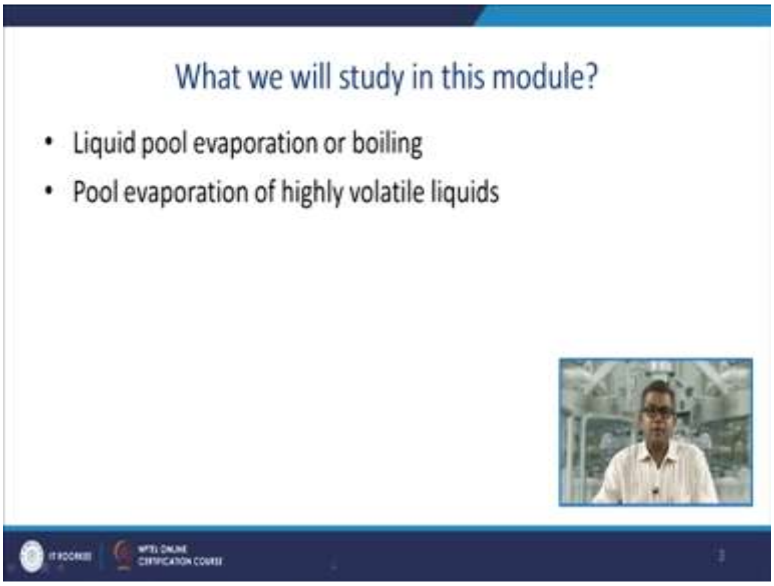

So, in this particular module we are going to discuss about the liquid pool evaporation or boiling, pool evaporation of highly volatile liquids. These two phenomena are extremely important in chemical engineering process industries and we are handling the liquid system. So, in the introduction part let us have a look that what is evaporation and a boiling.

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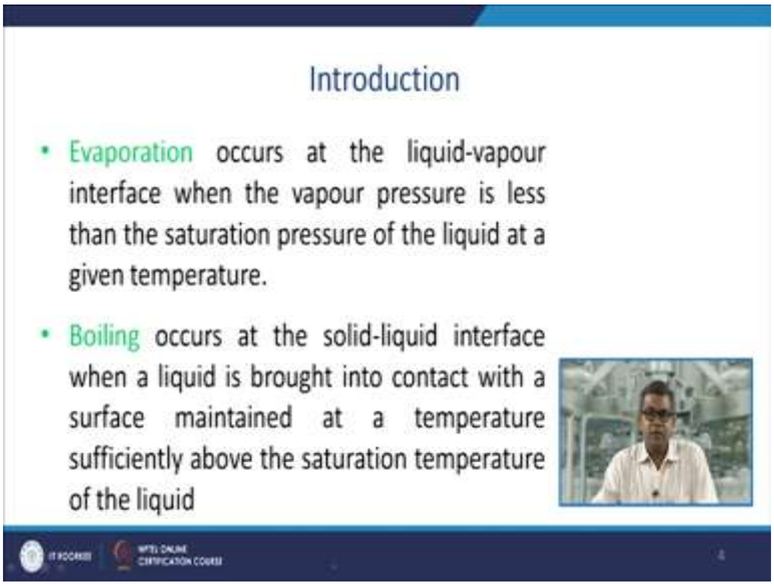

So, evaporation occurs at the liquid vapour interface when the vapour pressure is less than the saturation pressure of the liquid at a given temperature. Whereas boiling, this occurs at the solid-liquid interface when a liquid is brought into contact with a surface mentioned at a temperature sufficiently above the saturation temperature of the liquid. So, this is the basic difference between the evaporation and a boiling.

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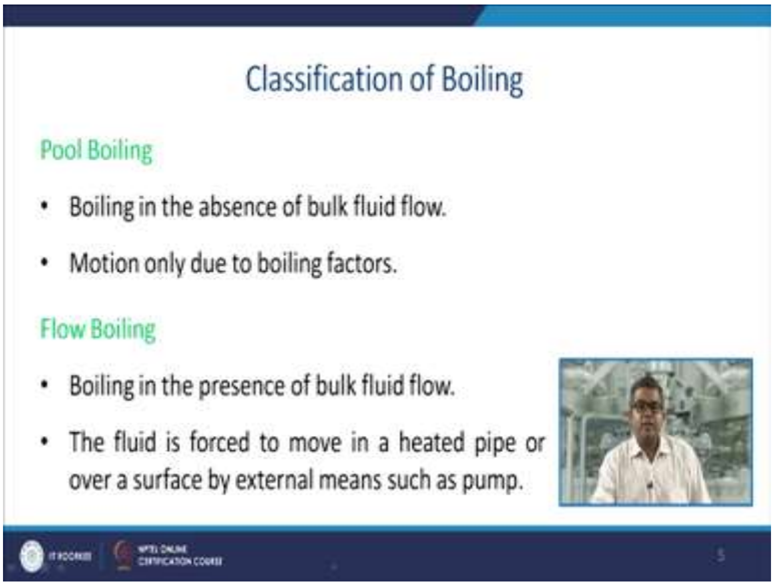

So, whenever we are considering the boiling, boiling is divided in two different categories like pool boiling, flow boiling. So, pool boiling, boiling, this is the boiling in the absence of bulk fluid flow where and motion only due to the boiling factors, so these are the this is related to the pool boiling. And we consider the flow boiling, the boiling is in the presence of bulk fluid flow and the fluid is forced to move in a heated pipe or over a surface by external means such as pump.

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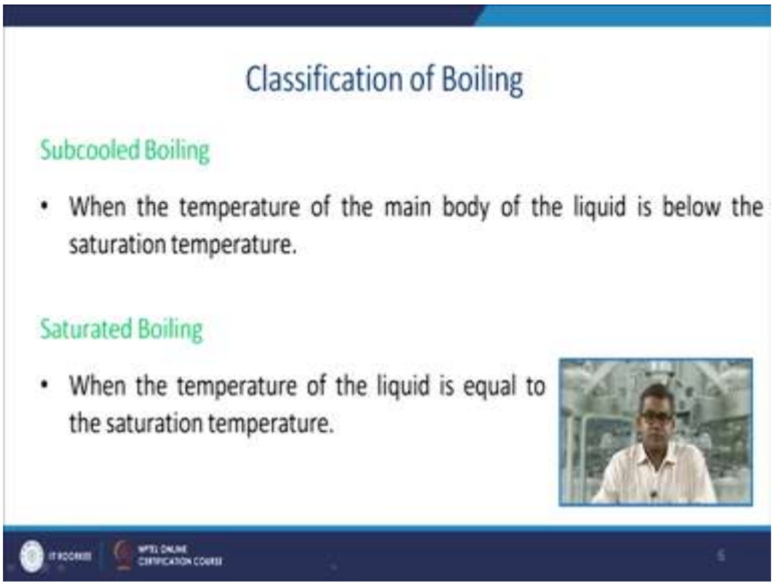

Another aspect is, the subcooled boiling, so usually occurs when a temperature of main body of the liquid is below the saturation temperature. Saturated boiling, when the temperature of the liquid is equal to the saturation temperature of the liquid in question. So, this is the difference between the subcooled boiling and a saturated boiling.

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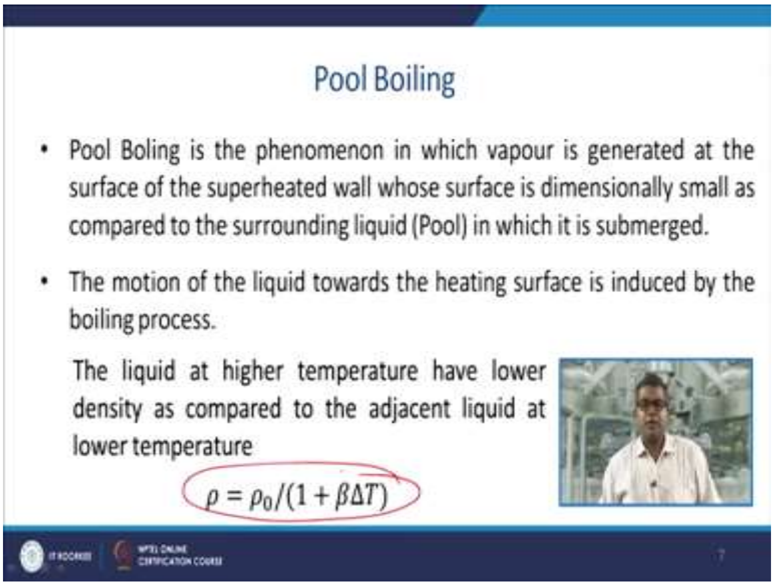

So, pool boiling usually is a phenomenon in which vapour is generated at the surface of a superheated wall whose surface is dimensionally small as compared to the surrounding liquid that is a pool in which it is submerged. So, the motion of the liquid towards the heating surface is induced by the boiling process. Now, the liquid at higher temperature have the lower density compare to the adjacent liquid at the lower temperature.

So, this is the governing equation for that particular segment.

$$\rho = \rho_0/(1+\beta\Delta T)$$

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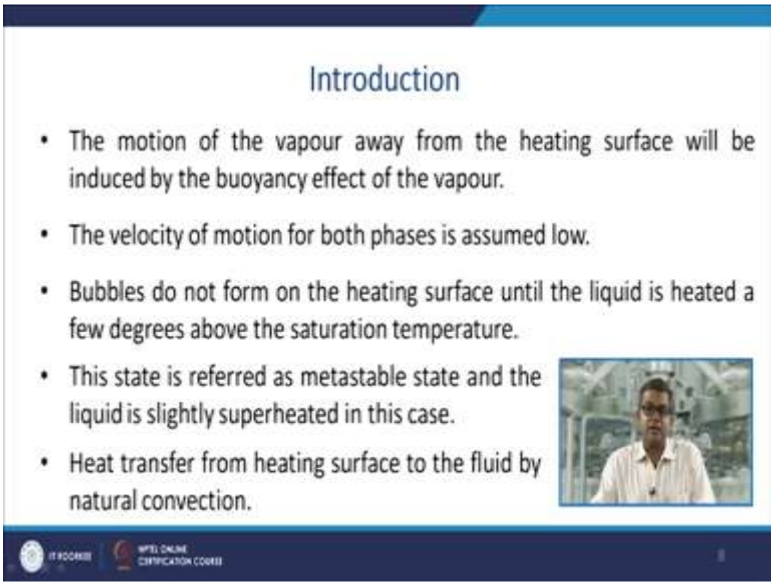

Now, the motion of the vapour away from the heating surface will be induced by the buoyancy effect of the vapour. So, the velocity of the motion for both phases is assumed low. Now, bubbles usually do not form on heating surface until the liquid is heated a few degree above the saturation temperature. Now, this particular state is referred as metastable state and the liquid is slightly superheated in that particular case.

Now, heat transfer from heating surface to the fluid by the natural convection, so usually this occurs by the natural convection.

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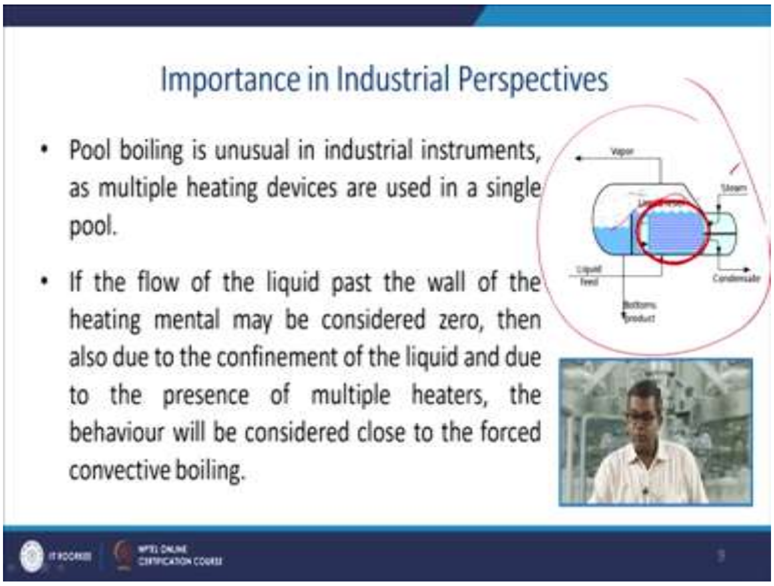

There are certain important industrial perspectives, now pool boiling is unusual in industrial instruments as multiple heating devices are used in single pool. Now, if a flow of liquid past the wall of the heating mental may be considered zero, then also due to the confinement of the liquid and due to the presence of multiple heaters, the behavior will be considered close to the forced convective boiling.

You can have a look in this particular diagram, there are, this is a typical heat exchanger, steam, condensate, bottom product liquid fuel and the boiling, here is a phenomenon of pool boiling.

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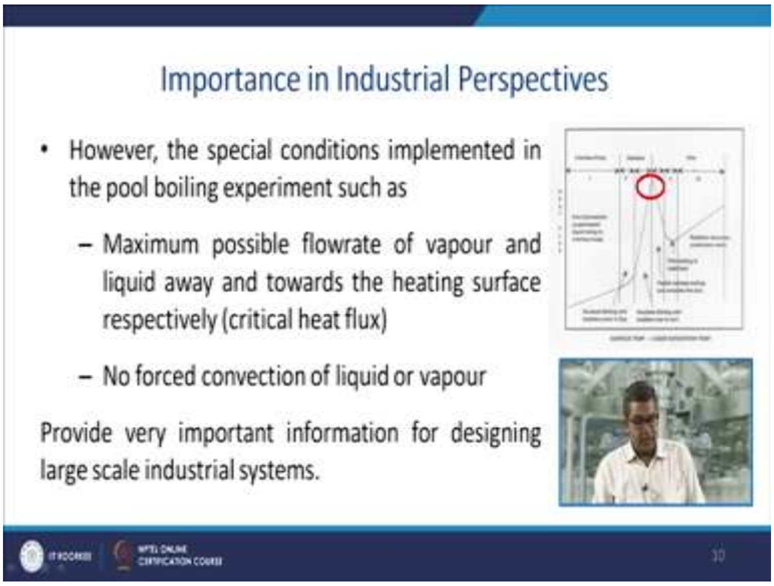

Now, however the special conditions usually implemented in the pool boiling experiments such as a maximum possible flow rate of vapour and a liquid away and towards the heating surface respectively that is called the critical heat flux and the no forced convection of liquid or vapour. So, provided very (impor) this provides a very important formation for designing the large scale industrial system.

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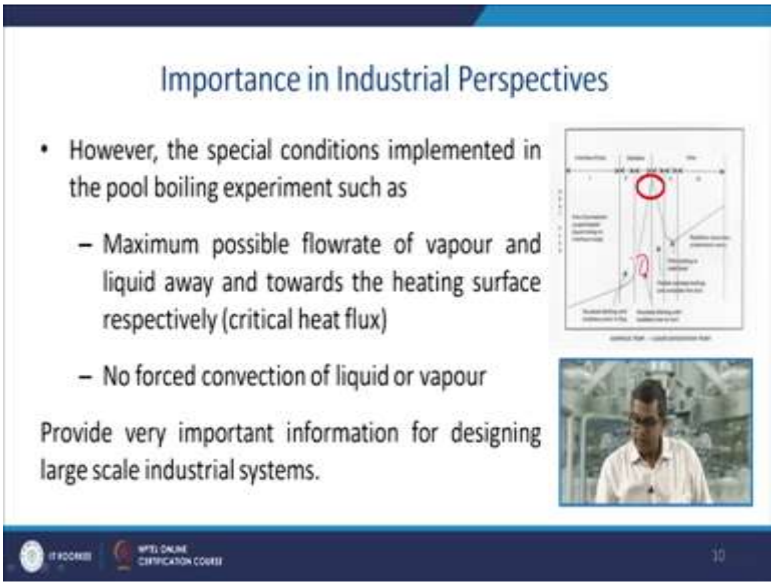

Now, the peak heat flux or burnout heat flux represents the upper limit of fully developed Nucleate boiling, you can have a look in this particular, this is a Nucleate (boiled) boiling zone, this one. So, while designing the engineering component, this heat flux provides the maximum limit of safe operation beyond this limit heat removal rate from the surface of heating device degrade substantially and this lead the melting or burnout of the surface.

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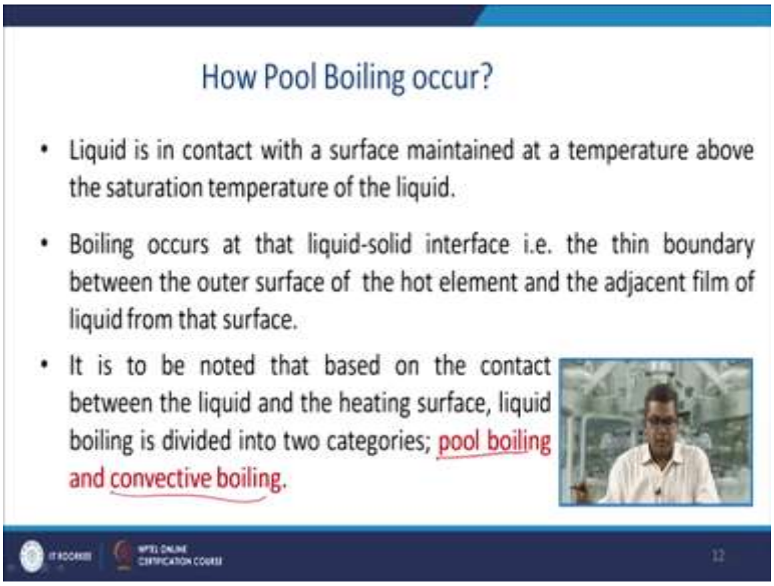

So, usual question arises that how this pool boiling occur? Now, liquid is in contact with the surface maintained at a temperature above the saturation temperature of the liquid, so boiling occurs at the liquid solid interface that is the thin boundary between the outer surface of the hot element and the adjacent film of liquid from the surface. Now, one thing to be noted that based on the contact between the liquid and heating surface, liquid boiling is divided into two categories one is, pool boiling and second is the, convective boiling.

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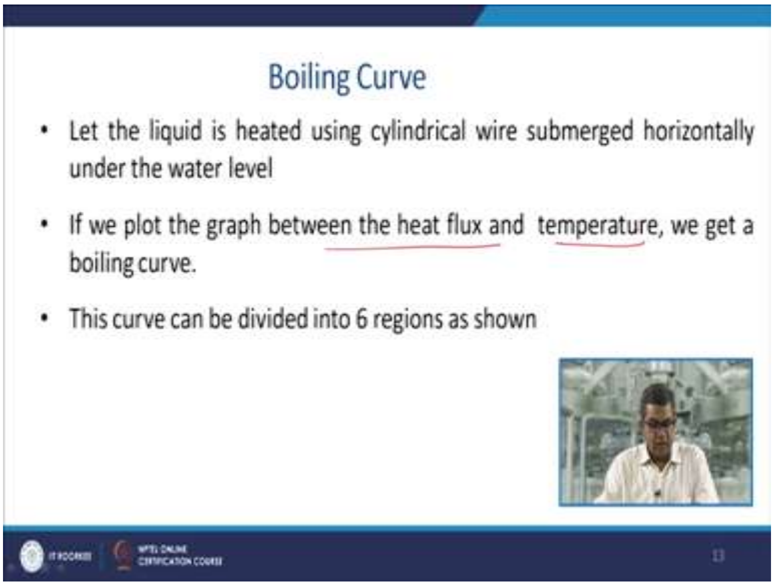

Now, sometimes we need to draw the boiling curve, so let the liquid is heating using the cylindrical wire submerged horizontally under the water level. Now, if you plot the graph between the heat flux and a temperature, we get a boiling curve. Now, this curve is between the heat flux and temperature.

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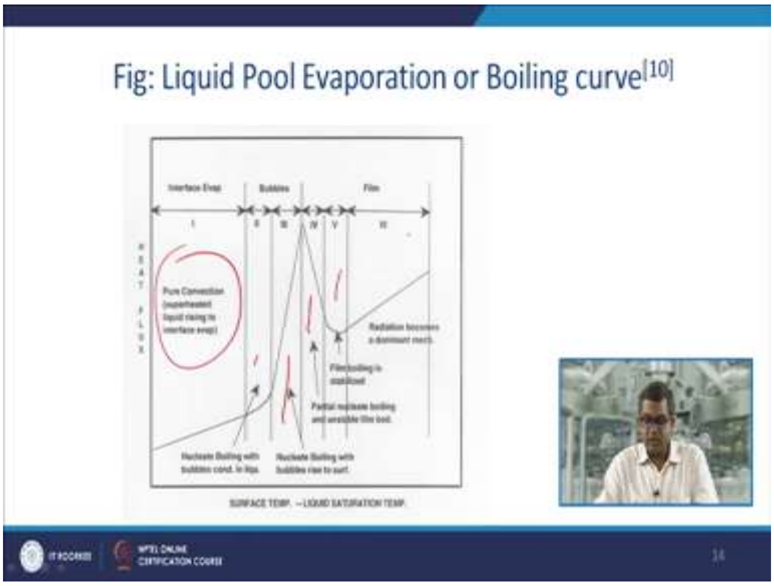

Now, this curve can be divided into six regions, which is represented here, region one, there the pure convection, superheated liquid rising to the interface, this is the Nucleate boiling with bubbles continued in the liquid, this one is the Nucleate boiling with the bubble rise to surface, this is the partial Nucleate boiling and unstable film boil, this is the film boiling is stabilized under these this fifth zone and the last zone is a radiation becomes dominant in this region.

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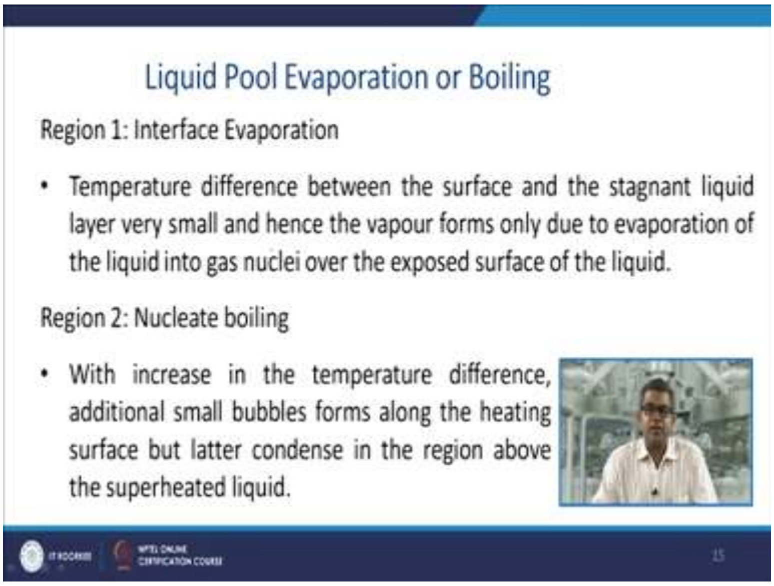

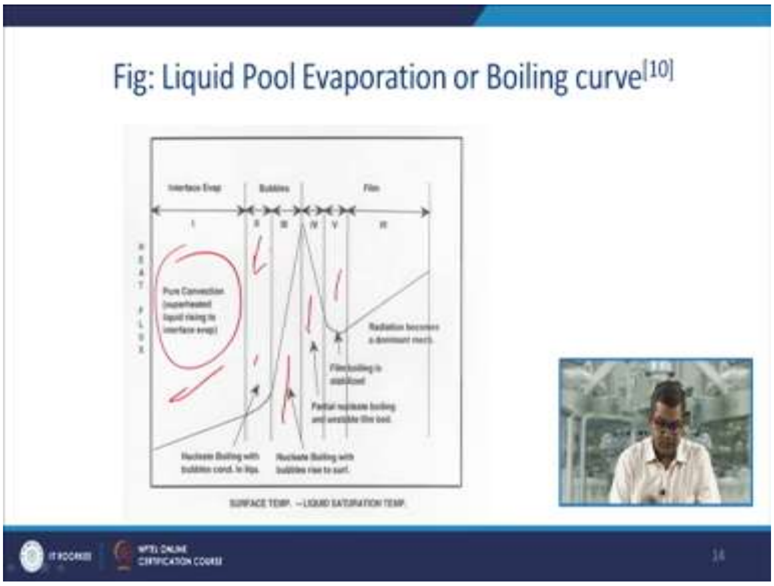

So let us have an elaborative approach of this particular plot. Now, let us consider this region one, this region one temperature difference between the surface and the stagnant liquid layer, very small, hence the vapour form only due to the evaporation of the liquid into gas nuclei over the exposed surface of the liquid, you can have a look of this particular region. Now, second region that is the Nucleate boiling this one.

Now, with increase the temperature difference additional small bubble form along the heating surface but later condense in the region above the superheated liquid.

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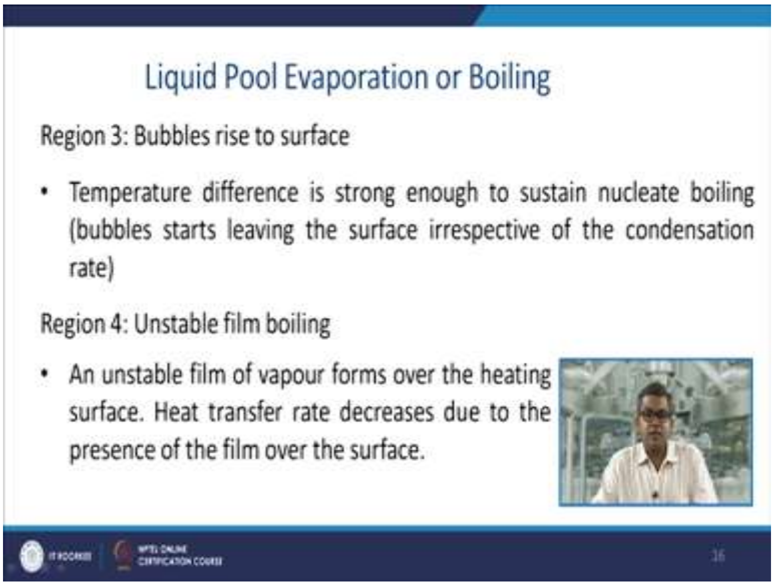

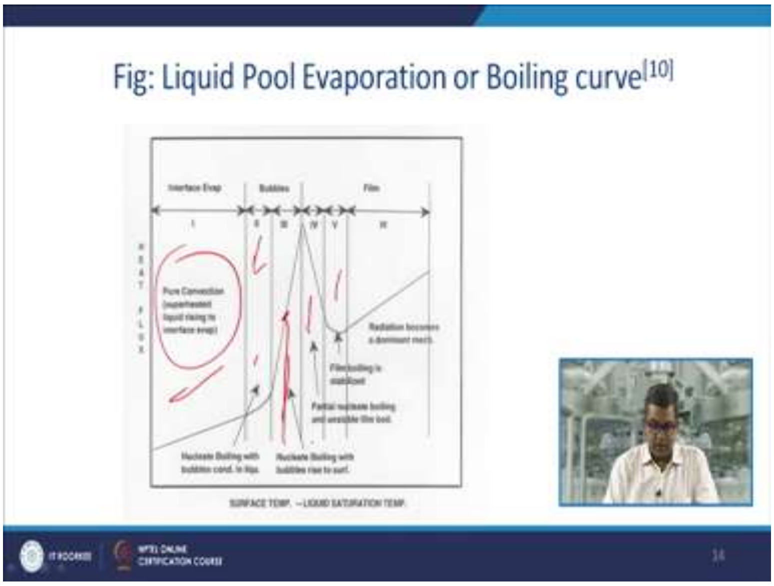

In the third region, that is bubble rise to the surface, this one, the bubbles rise to the surface. The temperature difference is a strong enough to sustain Nucleate boiling, bubbles start leaving the surface irrespective of the condensation rate. Now, in the fourth region, this one is the fourth region, now that is a unstable film boiling, the unstable film of vapour forms over the heating surface and a heat transfer rate decrease due to the presence of film over the surface.

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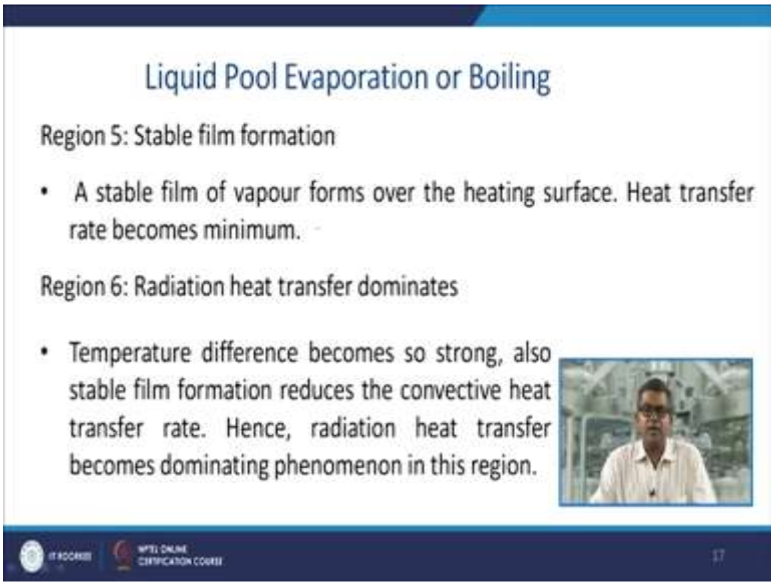

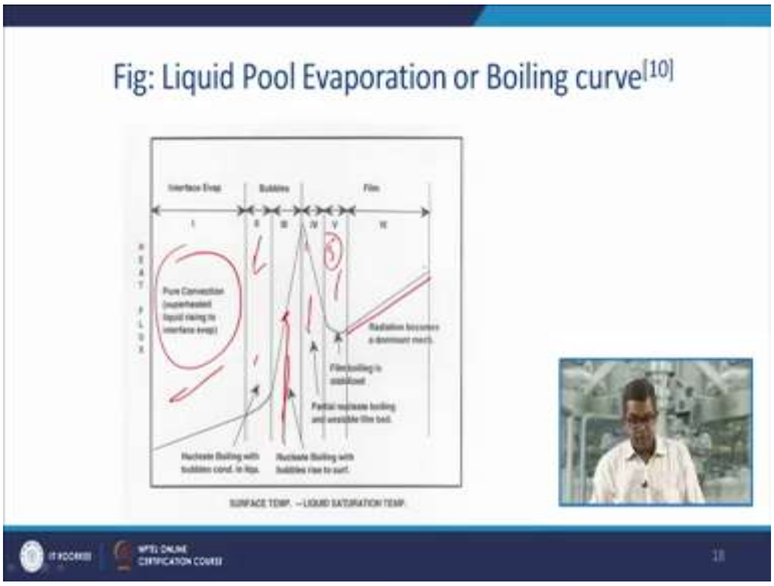

Now, the region five attributed to stable film formation. Now, you can see in this particular this is the region five. The stable film of vapour form over the heating surface and heat transfer rate becomes minimum. The last region that is, a radiation heat transfer dominants region, in this particular the radiation heat transfer dominates and temperature difference (become) becomes so strong, also stable film formation reduces the convection convective heat transfer rate.

Hence, the radiation heat transfer becomes dominating phenomenon in this particular region, you can have a look in this particular curve. So, this is the all the six regions of this particular phenomenon. Now, next is your pool evaporation of highly volatile liquids, this particular phenomenon is extremely common in process industry.

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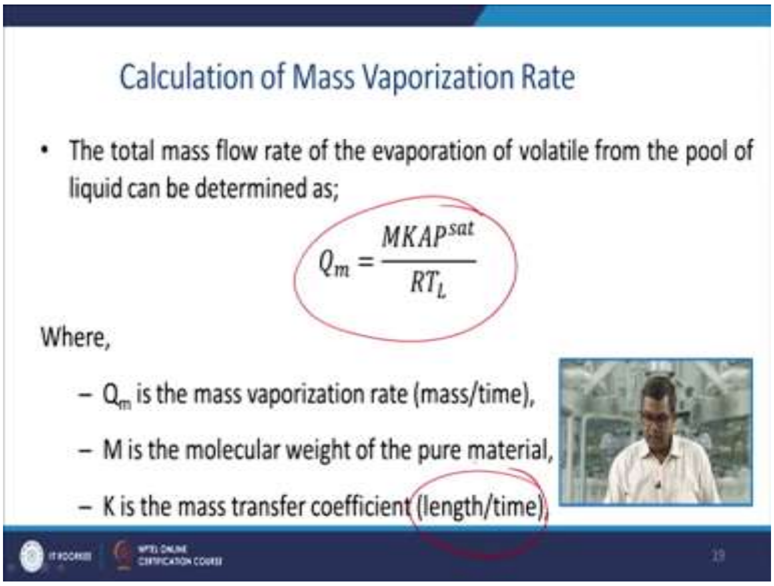

Now, for this the calculation of mass vaporization rate is carried out, so the total mass flow rate of evaporation of a volatile from the pool of a liquid, this is determined by this equation, earlier in different module we have derived this particular equation,

$$Q_m = \frac{MKAP^{sat}}{RT_L}$$

Q_m is the mass vaporization rate, that is the unit of mass per time, M is the molecular weight of the pure material, K is the mass transfer coefficient having the unit of length per time.

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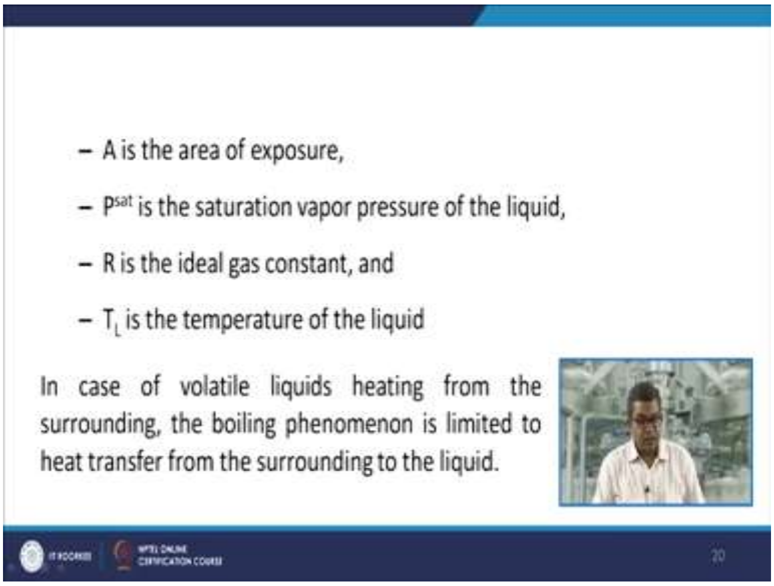

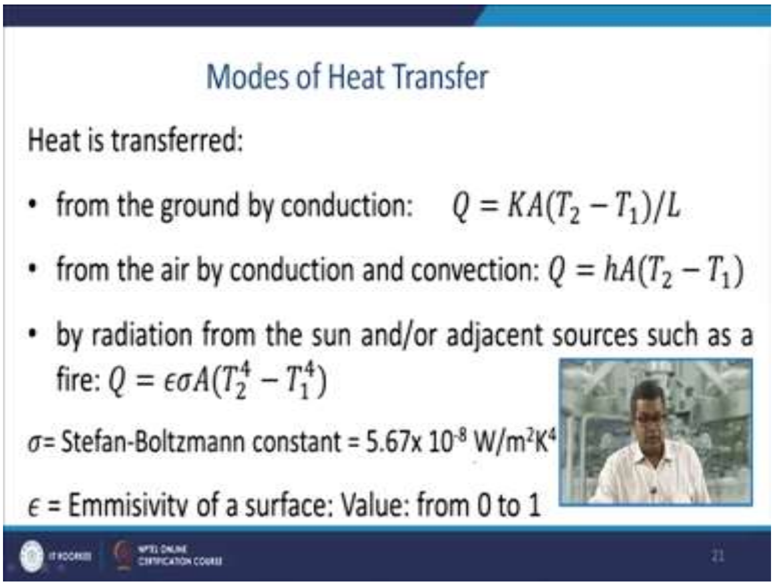

A is the area of exposure, P^{sat} (saturation) is the saturation vapor pressure of the liquid and R is the ideal gas constant and T_L is the temperature of the liquid. So, in case of volatile liquid heating from the surrounding, the boiling phenomenon is limited to heat transfer from the surrounding to the liquid.

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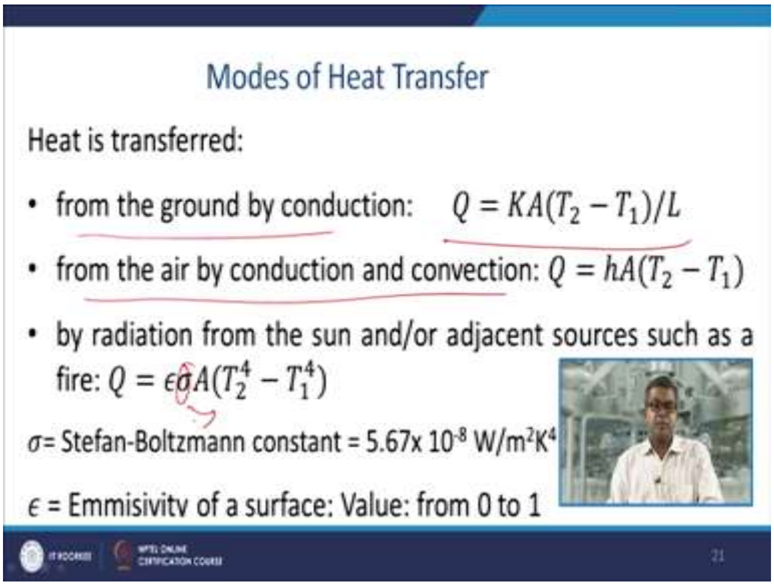

So, different modes of heat transfer while considering if this aspect then heat is transferred from the ground by the convection usual equation applicable is

$$Q = KA(T_2 - T_1)/L$$

Now, from air by conduction and convection

$$Q = hA(T_2 - T_1)$$

By radiation from the sun and adjacent sources such as fire, etcetera then

$$Q = \epsilon\sigma A(T_2^4 - T_1^4)$$

Now, this (σ) is the Stefan's Boltzmann constant having the value of 5.67 into 10^8 watt per meter square kelvin to the power 4, ε is the Emissivity of a surface value and usually values ranging from 0 to 1.

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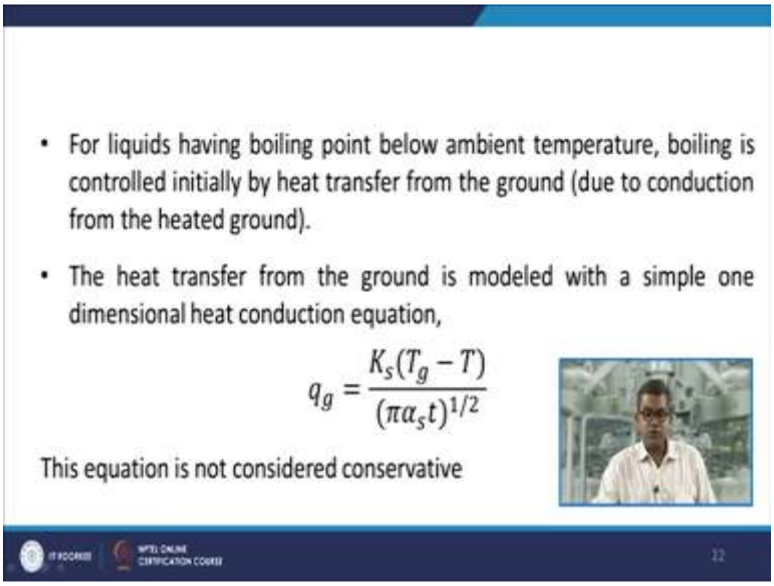

Now, for liquid having the boiling point below ambient temperature, boiling is controlled initially by heat transfer from the ground and due to the conduction from the heated ground. Now, the heat transfer from ground is modeled with a simple one dimensional heat conduction equation that is

$$q_g = \frac{K_s(T_g - T)}{(\pi\alpha_s t)^{1/2}}$$

this equation is not considered conservative.

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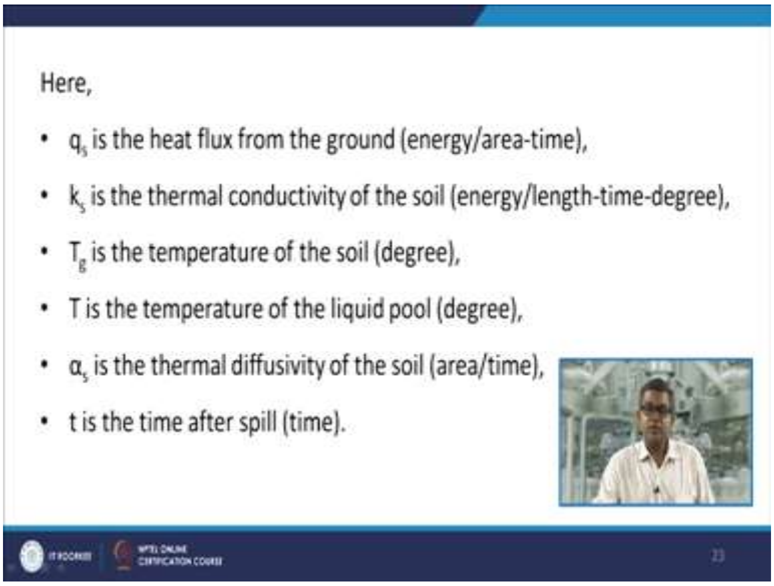

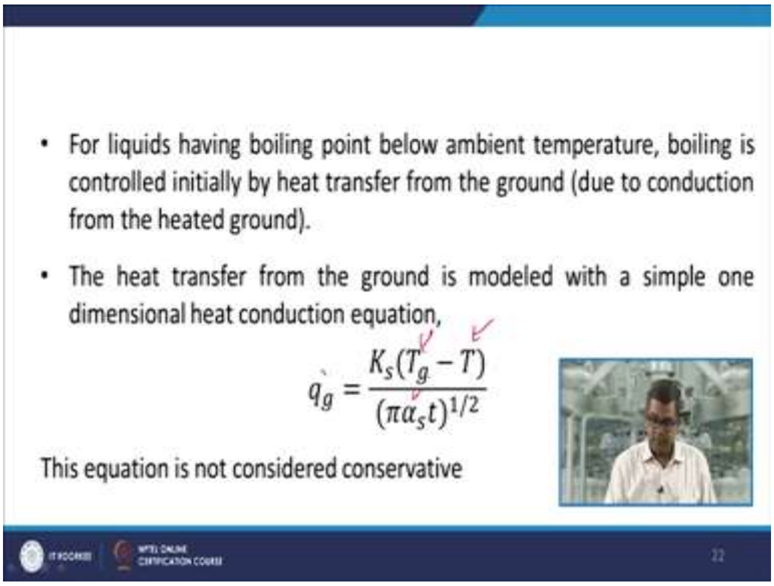

Now, here q_s is the heat flux from the ground energy having the unit of energy per area time. k_s is the thermal conductivity of the soil energy per unit length time and degree, T_g is the temperature of the soil in degree, this one. T is the temperature of the liquid pool in degree, this one, α_s is the thermal diffusivity of the soil having the unit of area per unit time and small t is the time after spill that is the unit of time, this one.

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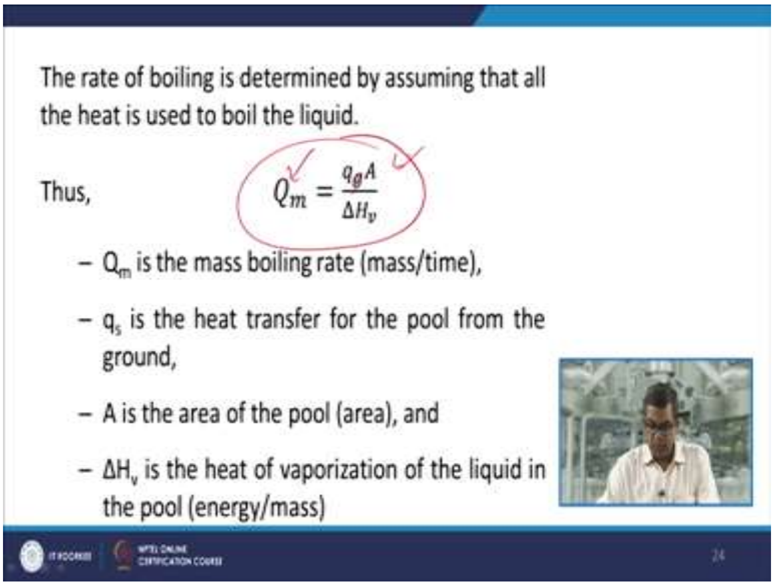

So, the rate of boiling is determined by assuming that all the heat is used to boil the liquid, that is thus, so

$$Q_m = \frac{q_g A}{\Delta H_v}$$

Q_m is the mass boiling rate, q_s is the this one, s is the heat transfer for the pool from the ground, A is the area of the pool and ΔH_v is the heat of vaporization of the liquid in the pool that is energy per unit mass.

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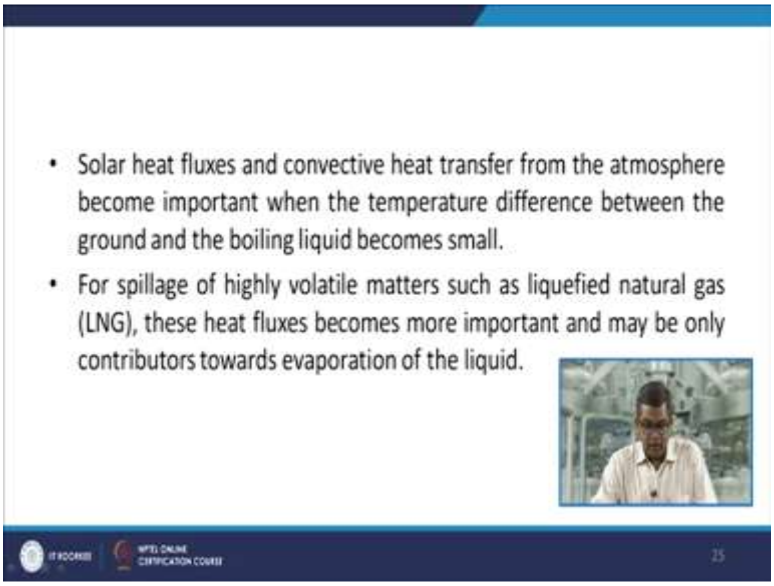

So, solar heat fluxes and convective heat transfer from atmosphere become important when the temperature difference between the ground and the boiling liquid becomes small. For spillage of high volatile matter such as liquefied natural gas, LNG, these heat fluxes become more important and may be only contributors towards the evaporation of the liquid.

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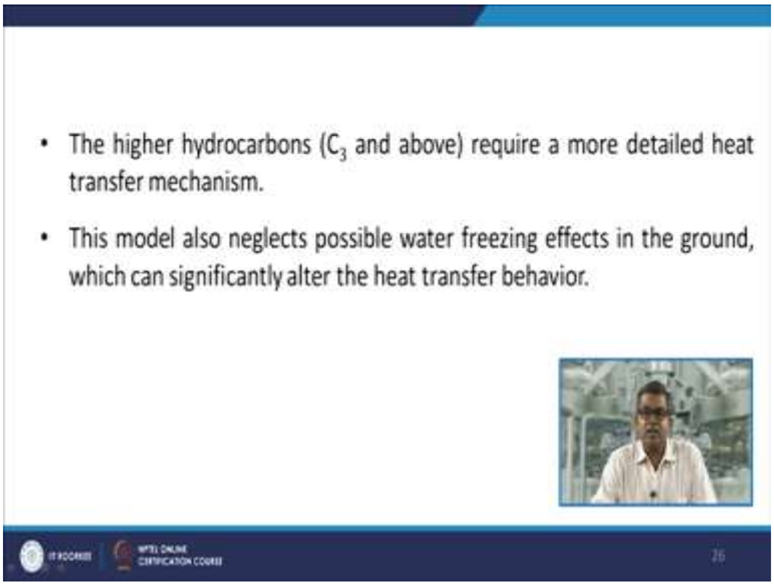

The higher hydrocarbons especially from C3 and above require a more detail heat transfer mechanism. Now, this model also neglects the possible water freezing effect in the ground and which can significantly alter the heat transfer behavior, this is very important phenomenon.

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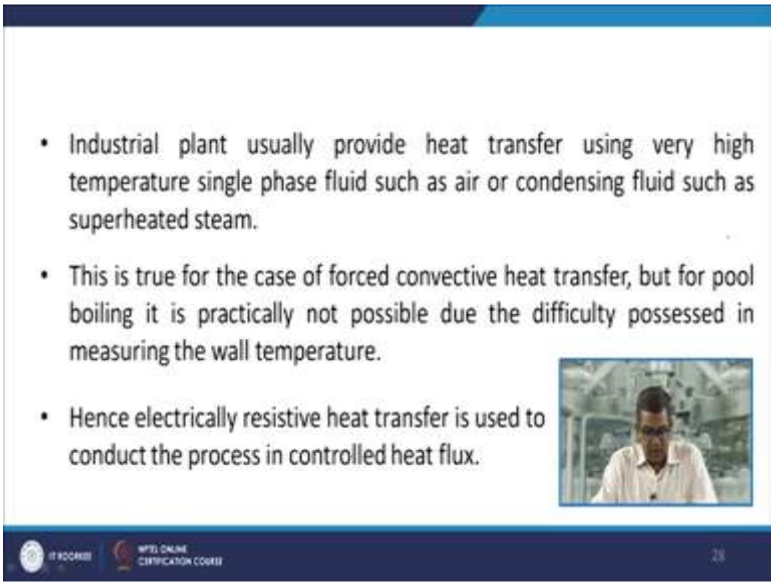

Now, let us have a look of different heat sources. So, industrial plant usually provide heat transfer using very high temperature single phase fluid such as air or a condensing fluid such as superheated steam. Now, this is true for the case of forced convective heat transfer but for pool boiling it is practically not at all possible due to the difficulty possessed in measuring the wall temperature.

Hence, electrically resistive heat transfer is used to conduct the process in controlled heat flux.

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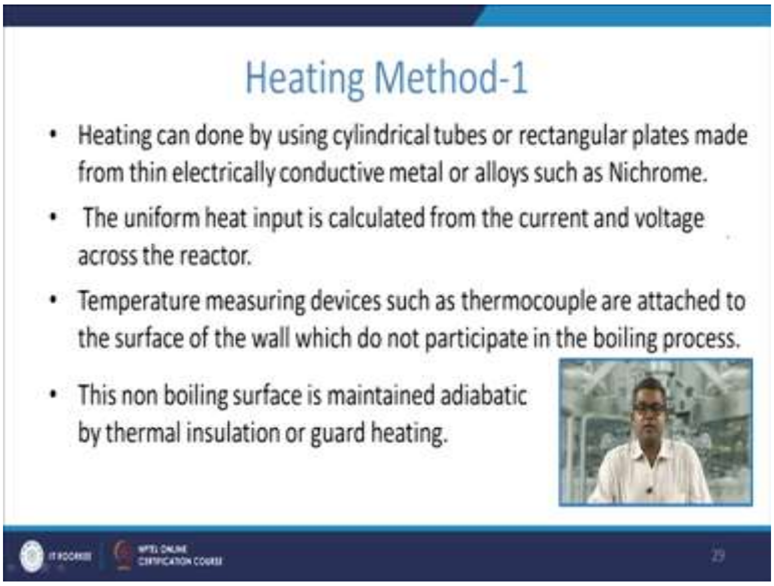

So, let us have different heating methods. So, in method number one, the heating can be done (use) using cylindrical tubes or rectangular plate mould made from thin electrically conductive material or metal or (allow) alloys such as Nichrome. The uniform heat input is calculated from the current and voltage across the reactor. The temperature measuring devices such as thermocouple are attached to the surface of the wall which is which do not participate in the boiling process.

Now, this non boiling surface is maintained adiabatic by thermal insulation or guard heating.

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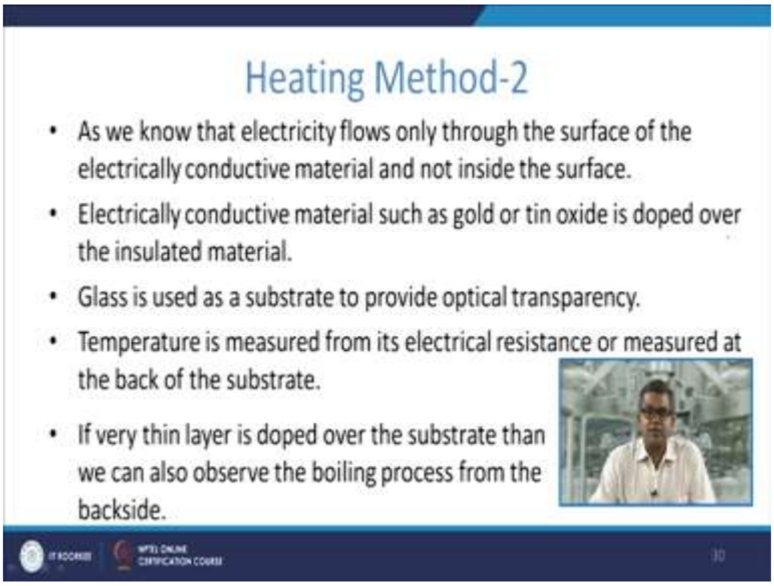

Another method attributed, now as we know that electricity flows only through the surface of electrically conductive material and not inside the surface. So, electrically conductive material such as gold or tin oxide is doped over the insulated material. Glass is used as a substrate to provide the optical transparency. Now, temperature is measured from its electrical resistance or measured at the back of the substrate.

A very thin layer is doped over the substrate then we can also observe the boiling process from the backside.

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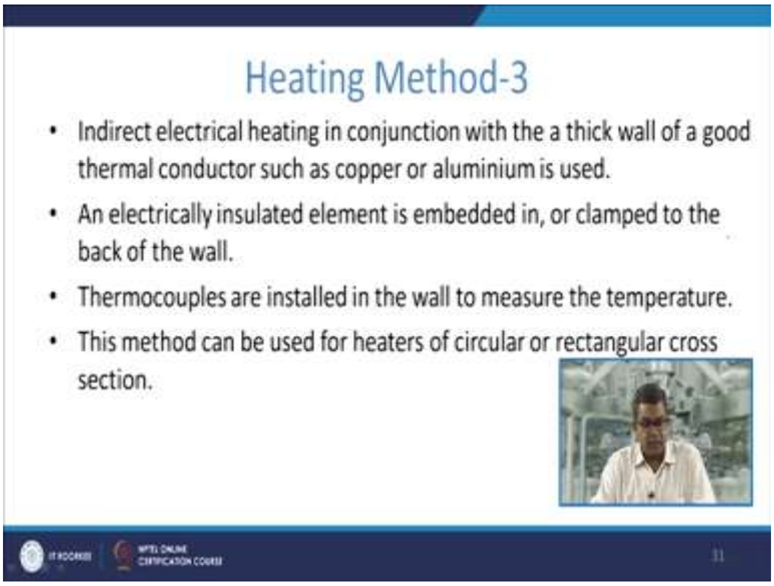

The third method is, the indirect electrical heating in conjunction with the, with the a thick wall of a good thermal conductor such as copper or aluminium. An electrically insulated element is embedded or clamped to the back of the wall. The thermocouples are installed in the wall to measure the temperature. Now, this method can be used for heater of circular or rectangular cross section.

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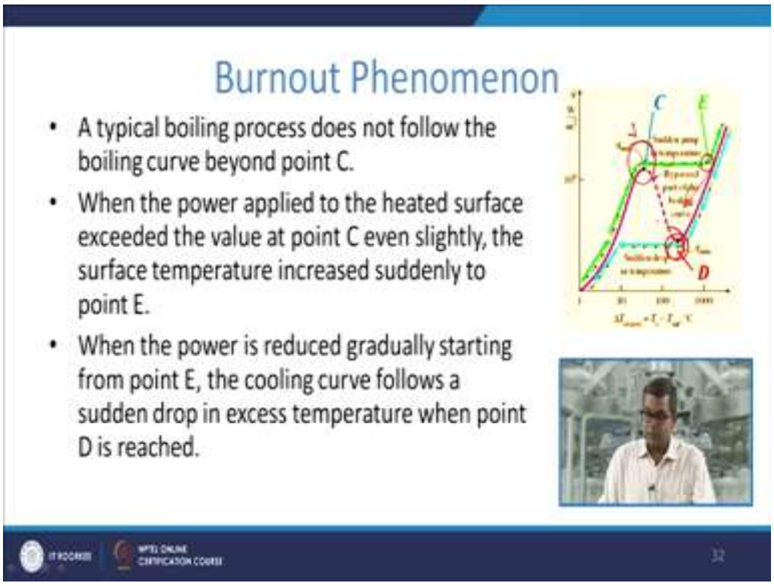

Now, let us have a look of burnout phenomenon. A typical boiling process usually does not follow the boiling curve beyond this particular point, point number C. So, when the power applied to the heated surface exceeded the value at point C, this one, even slightly, the surface temperature increased suddenly, now you can see here, to a point number E, this one. So, when the power is reduced gradually, starting from point this the cooling follows a sudden drop and the excess temperature when the point D is reached, this one, this point.

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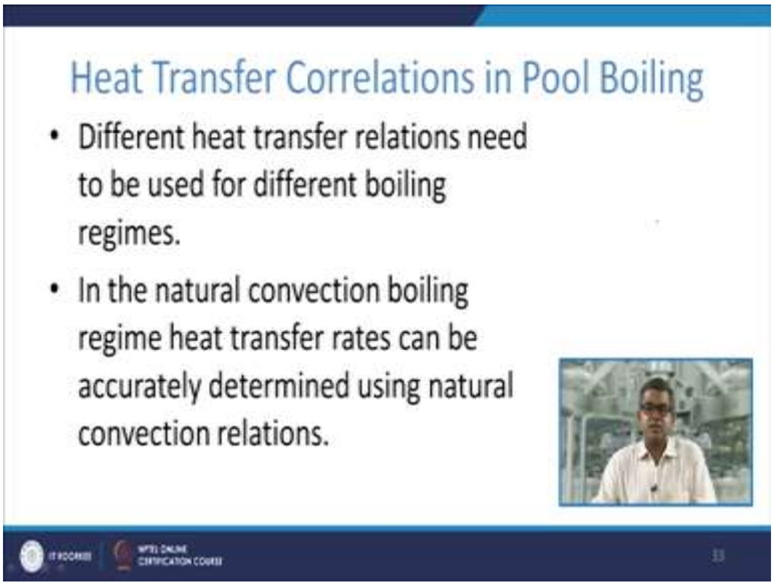

Now, let us have a look of heat transfer correlation in pool boiling. Now, different heat transfer relations need to be used for different boiling regimes. In the natural convection boiling regime heat transfer rates can be accurately determined using the natural convection relations.

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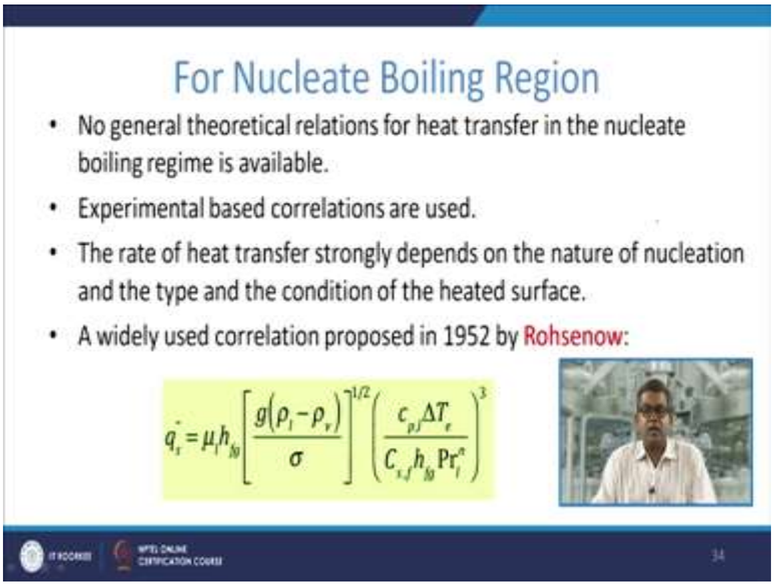

Now, let us have a look of the Nucleate boiling reason. There is no general theoretical relations for heat transfer in the Nucleate boiling regime. Experimental based correlations are sometimes used. The rate of heat transfer strongly depend on the nature of nucleation and the type and the condition of the heated surface.

A widely used correlation proposed by Rohsenow in 1952 is given by this particular equation

$$q_s^{"} = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{\frac{1}{2}} \left(\frac{C_{p,l}\Delta T_e}{C_{s,f}h_{fg}Pr_l^n}\right)^3$$

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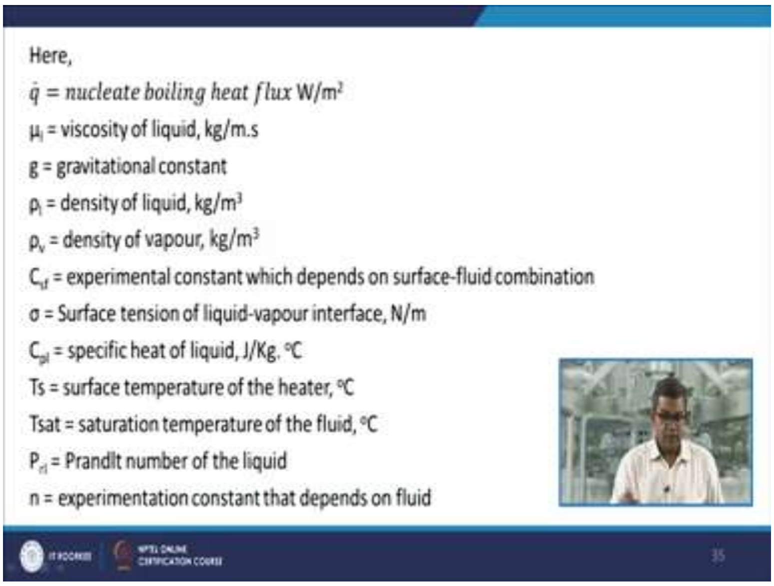

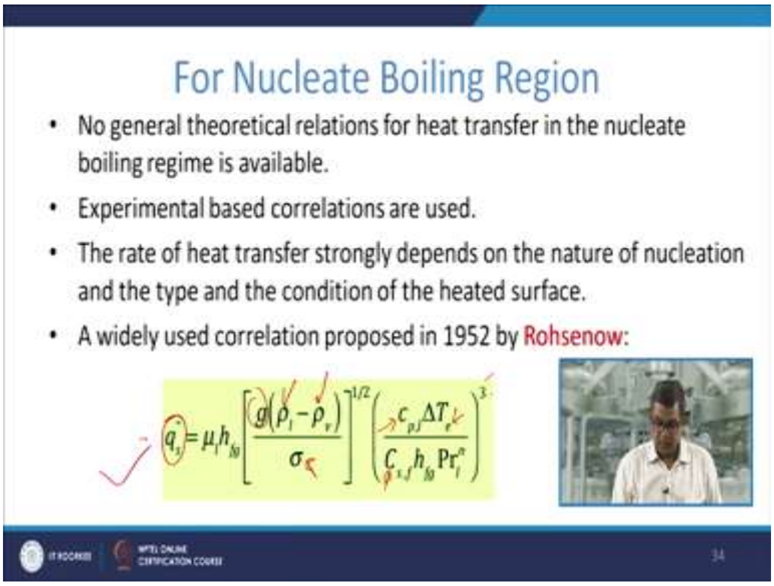

Now here,

$\dot{q}$ is the Nucleate boiling heat flux, this one, μ_l is the viscosity of the liquid in kilogram per meter second, g is the gravitational constant, ρ_l is the density of the liquid and ρ_v is the density of the vapour, C_{sf} is the experimental constant which depends on surface-fluid combination, this one. The surface tension of the liquid-vapour interface is this one then C_{pl} that is a specific heat of the liquid in Joule per kilogram degree Celsius, this one.

T_s is a surface temperature of the heater, T^{sat} (saturation) is a saturation temperature of the fluid in degree Celsius, P_{rl} is a Prandlt number of the liquid, n is the experimentation constant that depends on the fluid.

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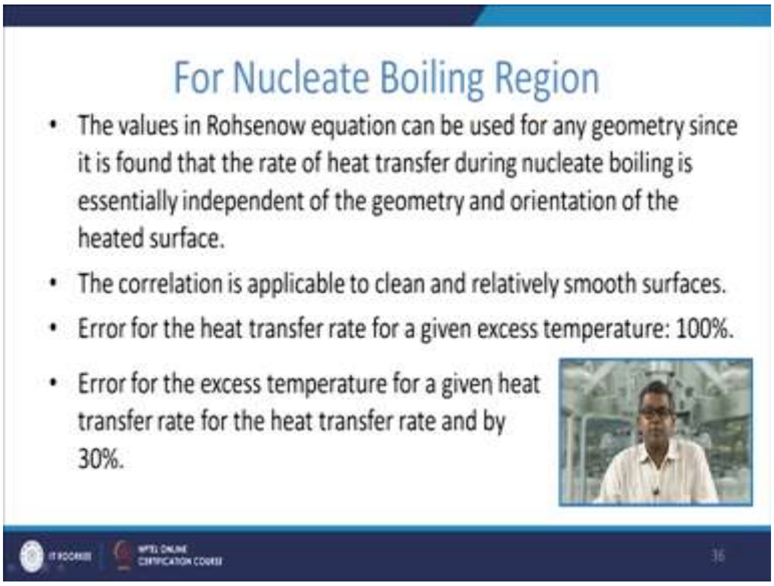

So, for Nucleate boiling region, the value of Rohsenow equation can be used for any geometry since it is found that the rate of heat transfer during the nucleate boiling is essentially independent of the geometry and orientation of the heated surface. The correlation is applicable to clean and relatively smooth surfaces. Error for heat transfer rate is given excess temperature that is, 100 percent. Error for the excess temperature for a given heat transfer rate for the heat transfer rate and by 30 percent.

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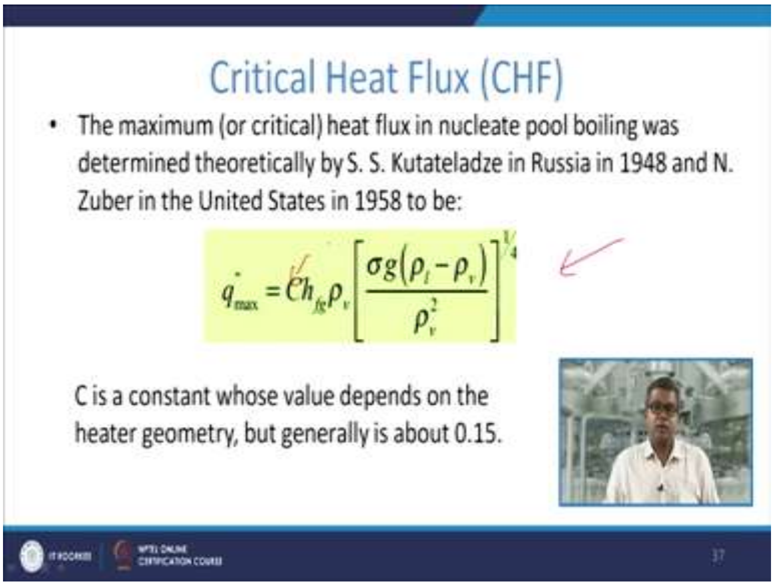

The critical heat flux, the maximum or critical heat flux in nucleate boiling was determined theoretically by S. S. Kutateladze in Russia in way back in 1948 and N. Zuber in the US in 1958. So, it is a represented by this particular equation,

$$q''_{max} = Ch_{fg}\rho_v[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}]^{1/4}$$

Now, here C is the constant whose value depends on the heater geometry but generally is about 0.15.

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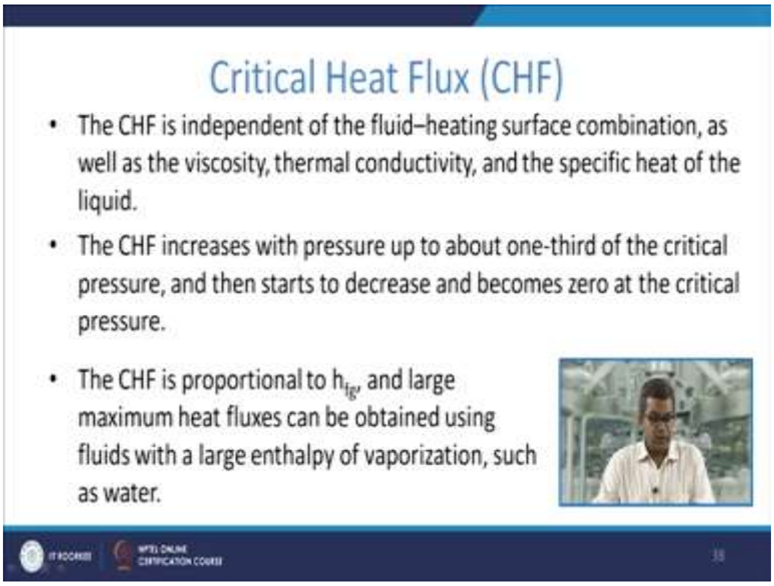

Now, this CHF that is the critical heat flux is independent of the fluid heating surface combination as well as the viscosity, thermal conductivity and the specific heat of the liquid. The CHF increases with the pressure up to about one-third of the critical pressure and then starts to decrease and becomes zero at the critical pressure. The CHF is proportional to h_{fg} and a large maximum heat fluxes can be obtained using the fluid with the large enthalpy of vaporization such as water.

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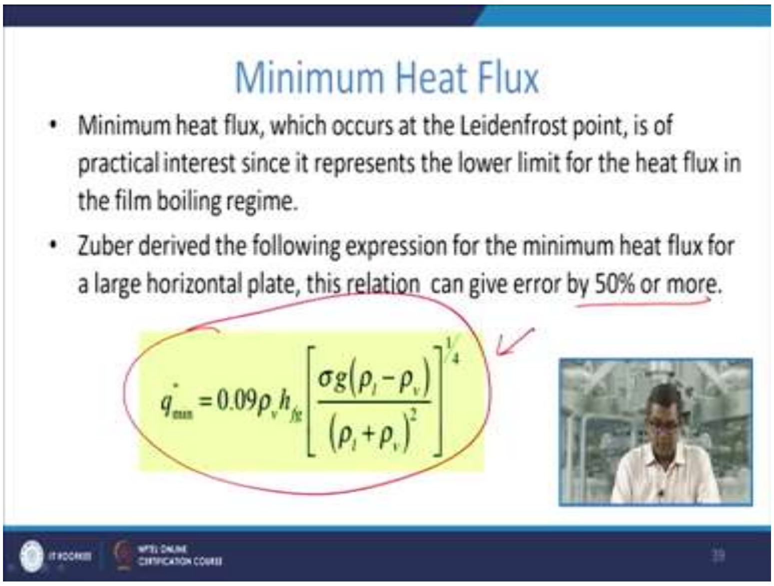

The minimum heat flux, the minimum heat flux, which occurs at the Leidenfrost point, is of the practical interest since it represents the lower limit of heat flux in the film boiling region. Now, Zuber derived this particular expression for the minimum heat flux for a large horizontal plate and this relation can be given by 50 percent or more.

$$q''_{min} = 0.09 h_{fg} \rho_v [\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}]^{1/4}$$

In this particular module, we have discussed the pool boiling, various aspects of pool boiling and a modeling aspect of a pool boiling.

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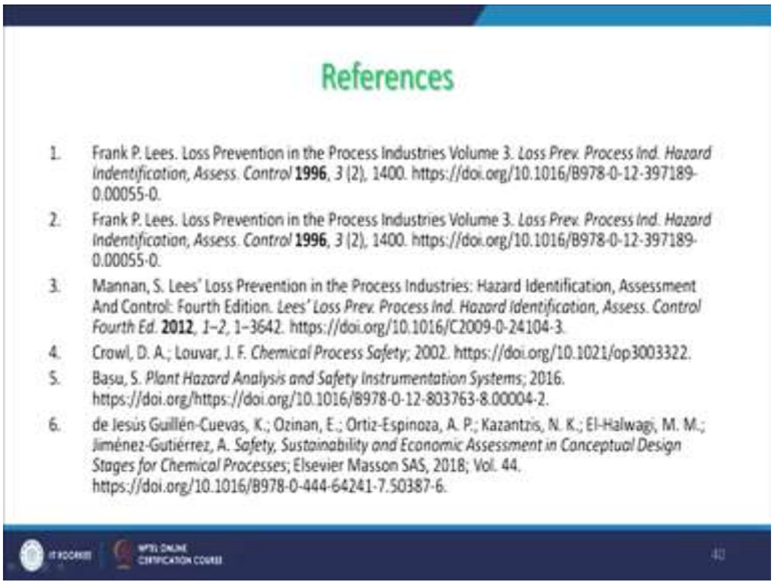

And in case of any query or a rift, you can always feel free to see these references we have listed.

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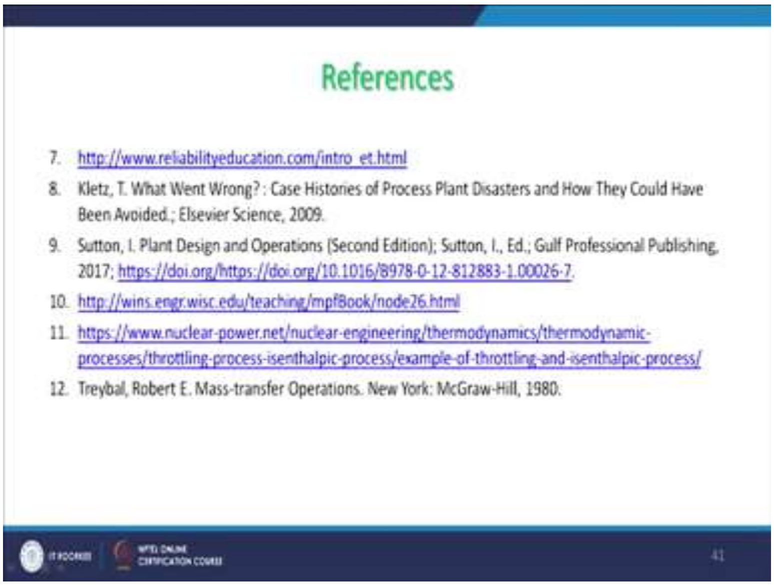

As or 12 references for the future study, thank you very much.