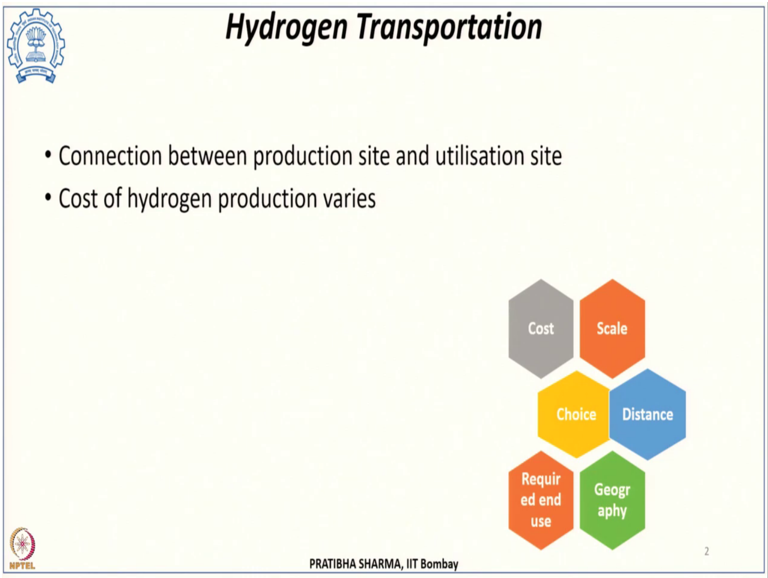
Hydrogen Energy: Production, Storage, Transportation and Safety
Prof. Pratibha Sharma
Department of Energy Science and Engineering
Indian Institute of Technology, Bombay

Lecture - 56
Hydrogen Transportation via H_2 Pipelines

We will start with a new section in this class that is on Hydrogen Transport.

(Refer Slide Time: 00:27)

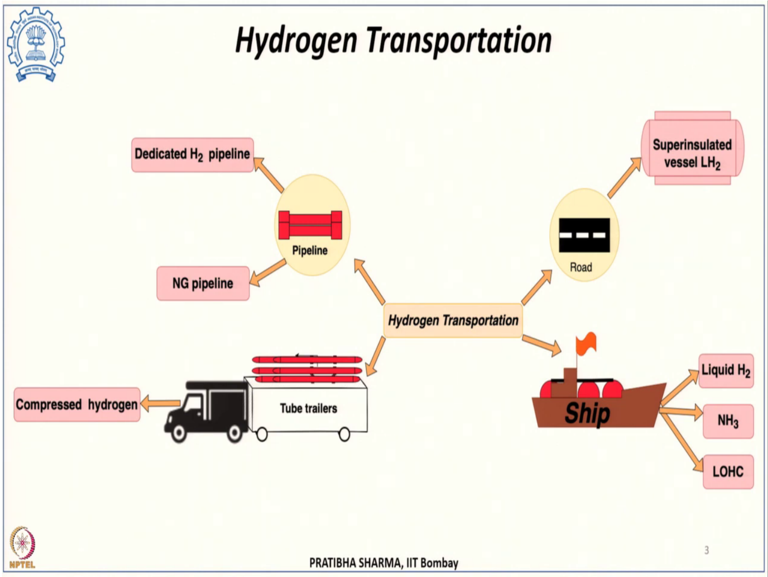


Now connecting the point of hydrogen production with the point of utilization is very much essential and their hydrogen transportation plays a major role. Now the low density of hydrogen that is the biggest bottleneck and that makes the hydrogen transportation very expensive. The options to tackle with this challenge is we can either compress we can either liquefy or we can incorporate hydrogen into larger molecules all these methods we have already studied.

Now, hydrogen can be transported either in the compressed gas form or in the liquefied hydrogen form or in higher density molecular liquid form.

.

(Refer Slide Time: 01:04)



Now for that either it can be carried in the form of compressed hydrogen through road by means, of tube trailers or it can be carried through pipelines. So, either we can use the existing natural gas pipelines for hydrogen transport or we can have new infrastructure with dedicated hydrogen pipelines or it can be taken over long distances in larger scale through ships as liquid hydrogen or it can be carried in form of liquid hydrogen through road using super insulated vessels.

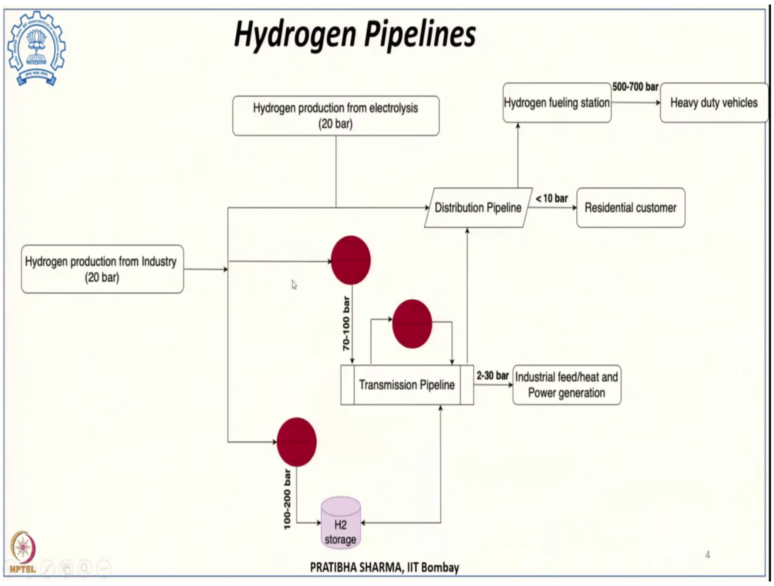
Now in this class we will be studying the option of hydrogen pipelines in detail. Now the transmission or the transport of hydrogen in large scale over longer distances that is attractive and that can promote even international trade. For example, some of the countries like Japan and South Korea their hydrogen demand will increase, but then the studies have shown that the green hydrogen production there it is not as economical as compared to the import of green hydrogen.

This is because of the limited locations available for installation of renewables and in that case the trade of hydrogen, the large scale long distance transport of hydrogen can play a major role. Now the choice of which particular method will depend upon what will be the volume the quantities that we want to carry for how long, what is the distance that we want to carry what is the geographical location and what is the end use for which we are going to use that hydrogen being transported.

.

And that also transportation makes it important because the cost of hydrogen production that also varies with the region it varies significantly with different regions. Now in this class we are going to specifically focus on the pipeline based hydrogen transportation.

(Refer Slide Time: 03:28)



Now, when it comes to pipeline based hydrogen transportation, the major advantages of pipeline transport are that they involve low operating cost, they have a long life 40 to 80 years, but the major disadvantages are they have a very high capital investment, capital cost. At the same time right of way is required and that makes the support of government as well as surety of demand essential if hydrogen has to be carried through pipelines.

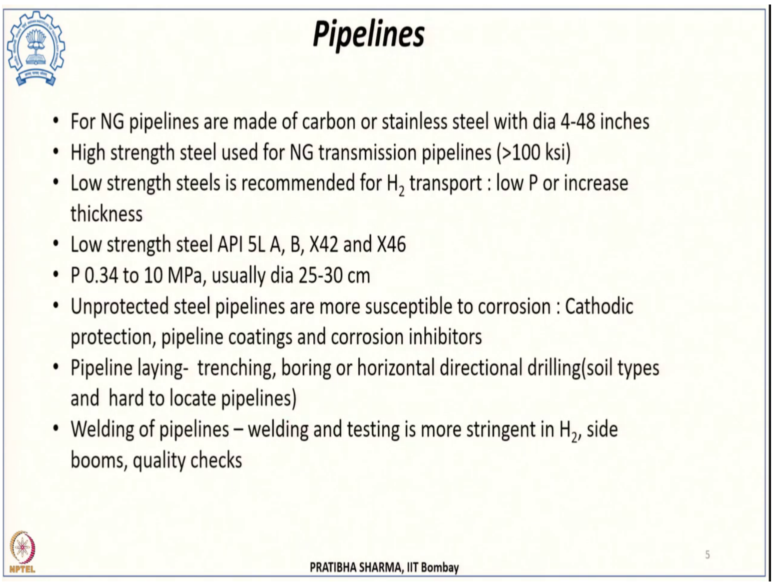
Now, the hydrogen can be carried from the point of production, through transmission pipelines and then it can go into the distribution pipelines. Now the flow of hydrogen through pipelines can occur because of a driving force which is the pressure difference. So, the pressure difference between the inlet and outlet and which is being maintained by compression.

So, there are compression stations and these compression stations depending upon what is the pressure required, what is the flow rate, what is the diameter of the pipeline, they may be located after every 100 to 500 kilometers. Now, these transmission pipelines they carry hydrogen and then they give it to distribution pipeline and that occurs at a city gate.

.

Now this city gate in fact, does a purpose of not only controlling the flow rate at the same time, reducing the pressure and also it meters how much amount of hydrogen is being delivered to the utility. So, as such there are different control rooms being established where the flow control, the pressure control these are being regulated or these are automatically controlled.

(Refer Slide Time: 05:23)



So, if we look at the different pipelines there are the larger diameter pipelines which are the transmission pipelines and then there could be distribution pipelines. Now as against the natural gas pipelines which are usually made up of carbon or carbon steel or stainless steel and they have a diameter of 4 to 48 inches, they are usually made up of high strength steel in which the strength being greater than 100 kilo pound per square inch, but these are subjected or more susceptible towards hydrogen embrittlement.

So, in case of hydrogen transport, low strength steel is being recommended. Now if we use a low strength steel; that means, we have a pressure limitation to which that could flow inside the pipelines so; that means, the operation will be either low pressure or if we want to raise that pressure then we will have to increase the thickness of the pipes and that may add up to the cost.

Or else we will have to use another materials like now being considered for a high pressure pipeline it could be same as we have studied in the high pressure tanks, it could be composites made used to make pipelines, but then it will become very expensive. So, for

.

hydrogen pipelines, low strength steel could be used, low grade steel could be used. So, the existing pipelines which are low grade or the low strength steel like API 5L A, B, X42 and X46 these can be used for hydrogen transport as well. The pressure in these pipelines ranges from 0.34 to 10 mega pascal.

And usually the diameter is 25 to 30 centimeter; however, that depends upon whether it is a transmission pipeline or whether it is a distribution pipeline or whether it is a service pipeline. The major important factor that we need to consider is corrosion protection of these pipelines. So, the unprotected steel pipelines when being used they are more susceptible to corrosion. So, the unprotected steel pipelines they may get corroded and can deteriorate very fast.

Now there are different ways to address this challenge one of the way is which is being used widely is the cathodic protection. And this has been used since 1930s. Now in this metal rod usually an anode that is installed in the proximity of the pipeline and that anode takes up the burden of corrosion and in that case it prevents the pipeline from corrosion and when that anodes gets corroded it could be replaced. Now the another option could be pipeline coating. So, both the external wall and internal wall both side coatings are being considered.

Now, if it is bare steel pipelines and when they are subjected to corrosive environment that deteriorates faster. So, in order to protect them from the corrosion usually a coating is being preferred. Now for like natural gas this coating could be fusion bonded epoxy or it could be like polyethylene, heat sink, sleeves these are being used for external coating.

There are also several coatings which are now being looked at for internal wall coating and these are to prevent hydrogen permeation or that could lead to hydrogen embrittlement another option could be addition of corrosion inhibitors. So, certain additives could be added in certain quantities to the gas flowing through the pipeline and that could prevent hydrogen embrittlement.

For example, the different inhibitors which have been studied for adding into the hydrogen these are like oxygen, carbonyl sulfide or it could be ethylene or it could be chloro-tri-fluoro ethylene, but the major challenge that remains with addition of these corrosion inhibitors is that not only adds to the cost because we are adding inhibitors to it.

At the same time, it could increase the toxicity, could increase the combust stability of the fuel and also at the point of usage then we will have to have additional separation and

.

purification to be integrated so, as to use it for applications. Now when it comes to laying down pipeline or burying the pipeline below the ground, there are different options which are available.

So, these pipelines can be buried below the ground before that the leveling of the surface or preparing the surface is done and that is done by means of cleaning and grading the working surface and thereafter it can be either buried by means of a process which is known as trenching. Now trenching usually, it is done to a depth and that depth depends upon the legal regulations.

Now depending upon whether the pipeline is a cross country pipeline or whether it is the inter country pipeline, within the country pipeline these legal regulations may vary and accordingly the trenching depth is decided. Now, one more method of laying down the pipeline could be either boring and an additional method could be Horizontal Directional Drilling.

So, HDD; however, these methods boring or HDD these are done when trenching is not possible or when trenching is not allowed. For example, this can be done if there is a paving road or there is a highway, there is a river in that case trenching is not done rather either boring or HDD is being done. But again there are certain restrictions there are certain challenges with boring or HDD, they may not be compatible with all soil types and at the same time sometimes it is difficult to identify some of the existing pipelines.

So, if there are certain hard to locate pipelines, then while drilling we may drill those existing pipelines. Now once the place is being ready these pipelines are being welded. Now these pipelines usually have several pipe sections and these pipe sections are welded together to make the complete pipeline. Now these pipe sections can also be either seamless, the seamless pipe sections can be made by either we can have hot working or can have piercing of the billets of solid steel or these can also be made from plates.

So, plates can be welded to form tubes and tubes, these are welded along the seam. So, the in case of hydrogen pipeline, the welding and testing is very important and it is much more stringent than in case of natural gas. So, this welding can be done by either TIG welding or MIG welding or laser beam methods. When these pipelines are laid down, so, during welding they have to be in line. So, as such equipment which is usually used is side booms.

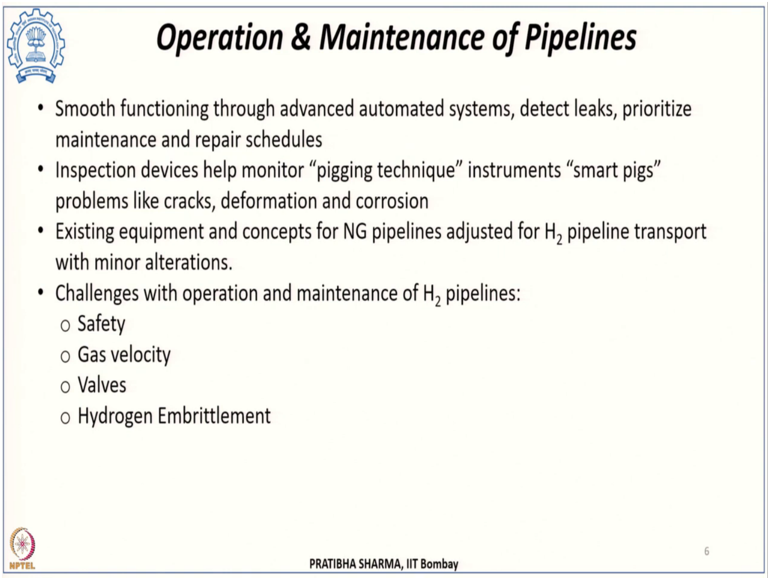
.

Now, once the entire pipeline is laid down then it has to be connected from initial point to the end point and during that process during after once it has been connected at that point lot of quality checks it has to go through. So, lot of testing has to be done and especially when it is hydrogen which is a very small molecule and much more prone to leakage. Now these quality checks are done by several test and inspections.

These can be radiological inspections, X-ray inspection or these can be ultrasonic inspection and when it is larger diameter or large stress pipelines, they undergo multiple levels of these checks. Once the pipelines these are ready then these has to be cleaned for the sand, for dirt, for the welding debris and then it has to undergo high pressure pressurized testing and then finally, it is dried with air before it is made operational.

Now not only laying down the pipeline, but operation and maintenance of pipeline is another aspect that we need to consider and it is important that smooth functioning of these pipelines is very essential.

(Refer Slide Time: 14:17)



Now this smooth functioning of pipeline is done through several advanced software and these are either fully automated software which are which are used to detect whether there are any leaks or to prioritize any maintenance or repair schedules.

And so, these are completely computerized analysis which is done to schedule all these maintenance, detection of leak, shutting down particular sections and regular inspections are very much important when it comes to maintenance of the pipelines. There are specialized equipments devices which can be used to monitor the pipelines like the technique which is used is known as pigging technique the instrument used is known as smart pigs.

And these smart pigs they are capable of finding out the problems like whether there is a crack present, whether there is any deformation or corrosion and then we need to take the preventive measures in order to avoid any accident. Already existing equipments and concepts which are there for the natural gas pipelines can be adjusted for hydrogen pipeline transport with a small or minor alterations they can still be compatible with the hydrogen based transport.

However, the major challenges that remains with the operation and maintenance of hydrogen pipeline are like the safety. The important one being safety, the reason being hydrogen is very small molecule and it is more susceptible to leak. At the same time the flammability limit we have learned in the very first lecture it is very wide for hydrogen the ignition energy for hydrogen is very small and hydrogen burns with a colorless flame and that makes taking all the precautions while transporting hydrogen very essential.

Secondly, the gas velocity. Now the volumetric capacity of hydrogen is 3.9 times lower than that of the natural gas or methane; that means, if we want to carry same energy through a given pipeline at a particular temperature and pressure the volumetric flow rate that will be required for hydrogen will be significantly high for hydrogen as compared to that for methane. Now this high volumetric flow rate that also leads to several challenges one it will require more of compression energy.

There are chances of leak at the same time when it is higher volumetric flow rate the hydrogen embrittlement could be significant. Now the valves, valves we know these are devices which control, which regulate, which allows the flow of gas. Now in case of larger diameter pipeline usually the valves used are motor operated valves. Now considering the hydrogen flow because so, as to get a tighter tolerance and to avoid hydrogen embrittlement exorbitant materials needs to be used for valves and that adds up to the cost.

So, these valves are more expensive than the ones used in natural gas pipelines. At the same time since hydrogen is a peculiar molecule as such continuous or frequent inspections maintenance and replacement of these valves is important and that further additionally adds

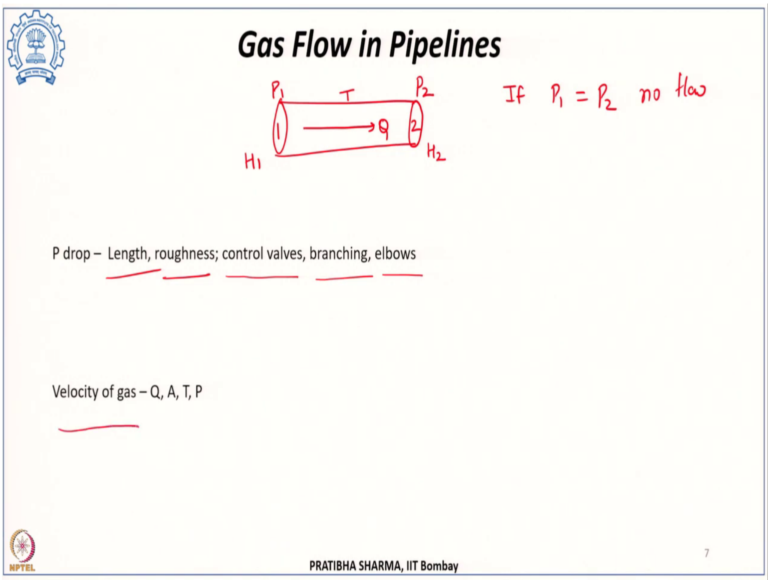
.

up to the cost. Another factor that is very important while selecting the materials is hydrogen embrittlement.

Hydrogen embrittlement is a process in which the material it loses its ductility and loses its tensile strength. So, what happens is, we have already seen that process where in a hydrogen molecule onto the metal surface dissociates into hydrogen atom, diffuses deep into the steel pipeline, goes into the grain boundaries creates stress intergranular cleavage and that could lead to rupture or crack now that could lead to the failure of the pipeline.

So, as such we have to use materials which are less susceptible to hydrogen embrittlement and then more frequent inspections operation and maintenance early detection of any problem is required and usually all these are automated systems already available for proper checking inspection and maintenance of the pipelines. Now let us consider the gas flow in a pipeline for that let us take a straight cylindrical section between point 1 and 2.

(Refer Slide Time: 19:13)



Such that the inlet pressure is P_1, outlet pressure is P_2, the elevation of point 1 is H1 that of point 2 is H2, the flow is Q, it is held at a temperature T. Now if we consider the flow inside a gas flow in a pipeline, we know that the flow of gas in a pipeline is because of pressure difference. If the two pressures are same then there will not be any flow of gas inside the pipeline.

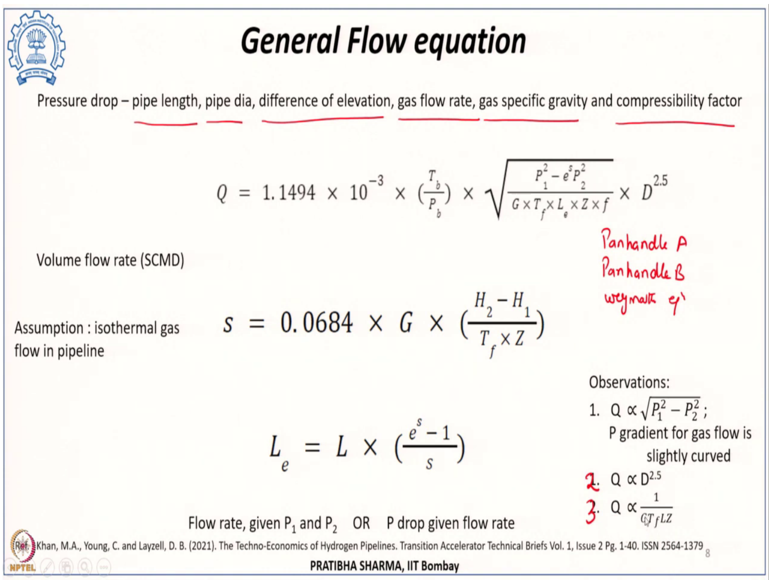
.

So, basically it is driven by the difference of pressure and that difference of pressure is provided by the compressors; however, partly this is being provided by elevation as well. Now when we consider this flow through the pipe there is a pressure drop which is being experienced during gas flow in pipelines. This pressure drop is because of the frictional losses. So, because of friction between the gas flow and the pipe there is a pressure drop and which depends upon the length and roughness of the pipe.

This can also increase because of the presence of control valves because of the branching and elbows present in the gas pipeline. This pressure drop needs to be reduced or compensated so, as to get a desired pressure at the outlet another important factor is the velocity of gas. Now this velocity of gas is proportional to the volumetric flow rate, the area of cross section, temperature and pressure.

Now, if we want to find out this pressure drop, Bernoulli's equation has been used to come up with a flow equation, that is the general flow equation or fundamental flow equation.

(Refer Slide Time: 21:30)



And that has been created using pipe length, pipe diameter, difference of elevations, gas flow rate, gas specific gravity and the compressibility factor. Now there are other equations that can also be used like the pan handle A, pan handle B or it could be Weymouth equation, all these can be used also for finding the pressure drop or flow rate.

.

However, the most widely used equation is the general flow equation or fundamental flow equation and this relates the volumetric flow rate with the different parameters. Now this has to refer to a standard as such this volume flow rate is measured in standard cubic meter per day. So, that is given by $1.1494\times10^{-3} \times T_b/P_b \times$ root of $[(P_1^2 - e^s P_2^2)/(GT_f L_e Zf)] \times D^{2.5}$.

Now, this T_b is the base temperature 288.7 K, P_b is the base pressure that is 101.3 kilo pascal, P_1 is the inlet pressure, P_2 is the outlet pressure and S is an elevation adjustment parameter, G is the specific gravity for hydrogen it is 0.0696, T_f is the average flow temperature, Le is the effective length, Z is the compressibility factor and f is the friction factor, here D is stands for the inside diameter.

Now, this elevation adjustment factor s is given by 0.0684 × G × [(H2 - H1), difference of elevation/ (the temperature, T_f × compressibility factor, Z] and the term Le, effective length is given by the length of the pipe, L × (e^s-1/s). So, the length of the pipe is L and the inner diameter of the pipe is D now this particular equation can be used to find out flow rate.

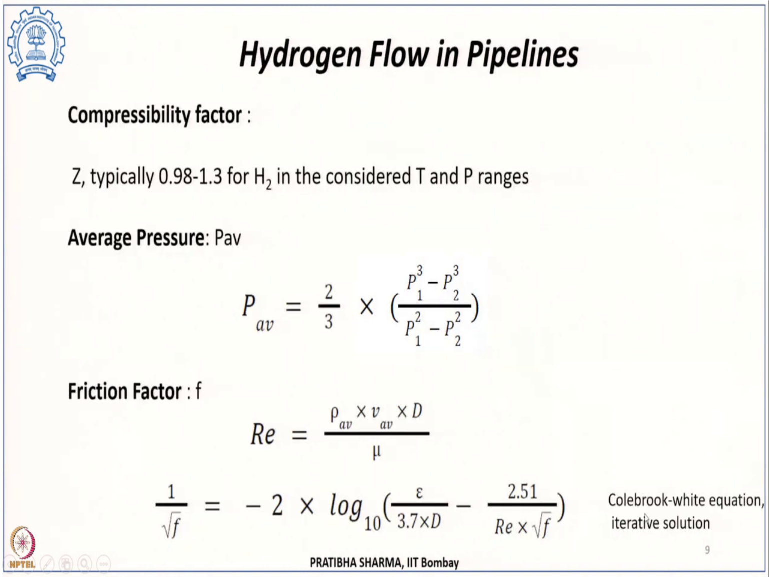
If inlet and outlet pressures are known or reverse if we want to find out the pressure drop in that case if the flow rate is given, we can find out the pressure drop the important assumption that lies in driving this equation is that the gas flow in the pipeline is isothermal and that is reasonably well because the pipelines are buried down below the ground usually they do not see very much fluctuations in the temperature.

Now, the important observations from this particular equation are, that this flow rate is proportional to root of $(P_1^2 - P_2^2)$ and; that means, that the pressure gradient for gas flow it is slightly curved as against the linear pressure gradient which is observed in case of liquids. The second thing which is important here is that the volumetric gas flow it is proportional to the $D^{2.5}$ or if the diameter of the pipeline increases the gas capacity or the flow rate increases.

The third important finding here is that the volume flow rate it is inversely proportional to the parameters like the specific gravity, the temperature, length and the compressibility factor. So, this is inversely proportional to these parameters. So, if these parameters decrease then the flow rate increases or vice versa.

.

(Refer Slide Time: 25:28)



Now, let us consider some of these parameters which are used in the fundamental gas flow equation. So, we have seen that there is a factor Z which is the compressibility factor and we have already learned in the previous classes that the compressibility factor tells the deviation from the ideal gas behavior. Under the considered temperature and pressure ranges which we consider in the hydrogen gas pipelines, this value of compressibility factor lies in the range of 0.98 to 1.3 and this can be calculated through various tools.

The another parameter is average pressure and that is given by 2/3 $[(P_1^3 - P_2^3)/(P_1^2 - P_2^2)]$. The friction factor that we have seen in the general flow equation that can also be found. Now the gas flow in the pipeline can be categorized into either laminar, turbulent or transitioning from laminar to turbulent based on the dimensionless parameter which is the Reynolds number.

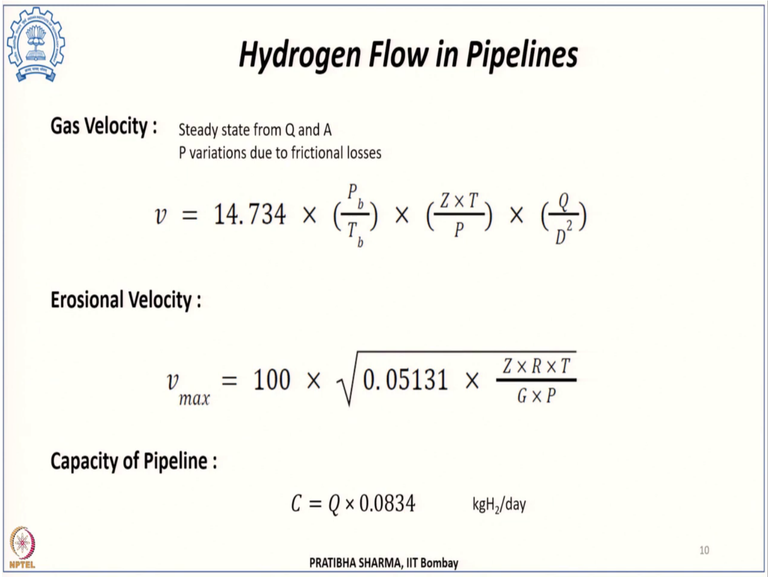
Usually for gas flow in the pipeline for hydrogen flow in the pipeline under the considered temperature and pressure ranges this is in the turbulent flow regime. It depends upon the gas property, the average velocity, inner diameter of the pipeline and the gas viscosity. So, these are this is the average density, average velocity of the gas flow, diameter of the pipeline and the gas viscosity.

So, the friction factor this can be either found from the moody friction factor curves graphs or it can also be found from the Colebrook white equation. So, it is 1/root f is given by -2 $\log_{10}$ ((ε/3.7D) – (2.51/(Re × root of (f)))). So, the friction factor, it in fact, depends upon the inner

.

wall of the pipeline. So, it depends upon the diameter, the surface roughness of the pipeline as well as whether the flow is laminar or turbulent.

(Refer Slide Time: 27:44)



Another characteristic that needs to be considered is the gas velocity. If we consider the flow to be steady state in that case it can be derived from either like the volume flow rate and the area of cross section at a given temperature and pressure; however, since during considering the flow inside a pipeline, the pressure variations which arises because of the frictional losses, this velocity also changes and that velocity can be given by this particular relationship.

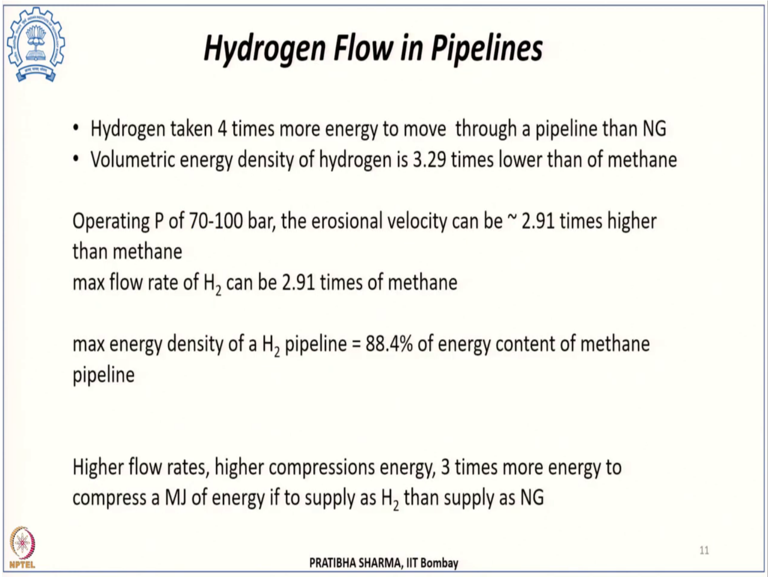
So, the velocity of the gas inside the pipeline that is inversely proportional to pressure, it depends upon compressibility factor, temperature, flow rate and diameter. It is given by $14.734 \times P_b/T_b \times ((Z\times T)/P) \times Q/D^2$ where P_b is the base pressure, T_b is the base temperature, Z is the compressibility factor, T temperature, P pressure volume flow rate and the inner diameter.

Now there is a limit to which this maximum velocity is allowable beyond that there is an erosion of the inside valves of gas pipeline that could occur if it is exposed for a longer time. So, that maximum velocity is known as the erosional velocity. So, the v_{max} is given by $100 \times$ root of $[0.5131 \times ((ZRT)/GP)]$. So, all these we have already known what are these terms standing for finally, we can also find what is the capacity of the pipeline.

.

So, the capacity is given by the volume flow rate which is standard cubic meter per day and a conversion factor to convert it into kg of hydrogen per day. So, that is Q × 0.0834.

(Refer Slide Time: 29:37)



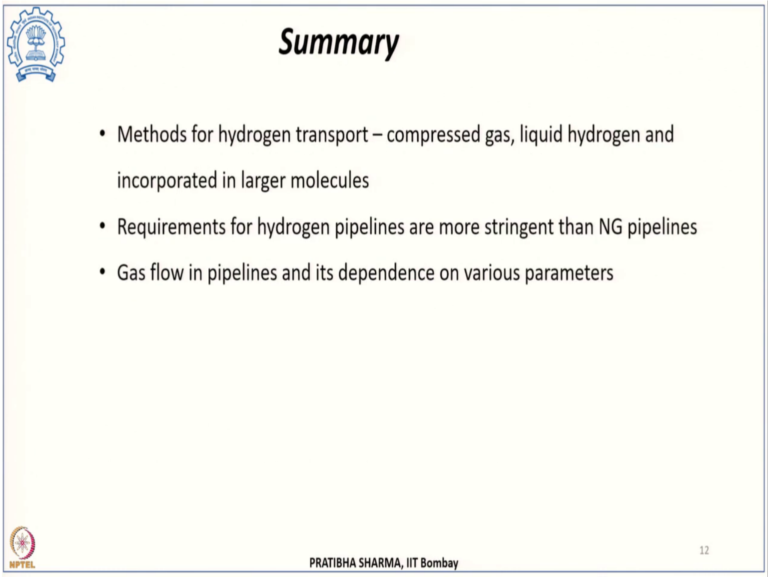
Now, when we consider hydrogen flow in pipelines, we know that it takes more energy to flow hydrogen as compared to natural gas through a pipeline. So, it is roughly around 4 times more energy to move hydrogen in a pipeline. We also know that the volumetric energy density for hydrogen is 3.29 times lower than that of methane.

If we consider that the operating pressure of hydrogen in the pipeline is between 70 to 100 bars and taking the erosional velocity to be approximately 2.91 times more than that of methane which is allowed in that case the maximum flow rate for hydrogen could be 2.91 times that of methane which could provide us that the maximum energy density of hydrogen in that pipeline or a given pipeline at a certain temperature and pressure is 88.4 percent of the energy content of methane.

So, this is simply 2.91 divided by 3.29. Now if we want to have higher energy content or higher flow, in that case it will require more of compression energy and that compression energy roughly it is 3 times more mega joule of energy if we want to supply hydrogen as against supplying the natural gas.

.

(Refer Slide Time: 31:02)



To summarize in this class, we have seen the different methods of hydrogen transport that could be used like the transport in the form of compressed gas as liquid hydrogen and it can also be incorporated into larger molecules transported over long distances as liquids. We have seen specifically the transport of hydrogen in hydrogen pipelines and the requirements for hydrogen pipelines these are more stringent than the natural gas pipelines.

We have seen the gas flow equation as well as the dependence of this gas flow on to the various parameters when being transported through a gas pipeline.

Thank you.