

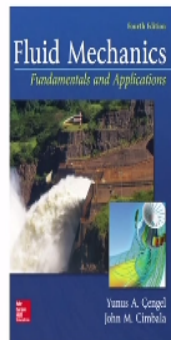
Fluid Mechanics
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Lecture - 20
Dimension Analysis and Similarity

Welcome all of you for this lectures on fluid mechanics and today we will discuss about dimension analysis and the similarity.

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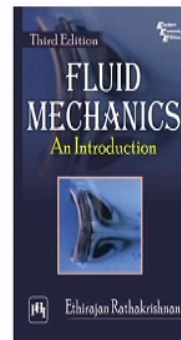
Reference Books for the Course



Yunus A. Cengel
John M. Cimbala



Frank M. White



Ethirajan Rathakrishnan

I have been following these 3 reference books, but the mostly today I will talk about the professor Radhakrishnan's books, which is one of the (()) (00:53) on the dimension analysis and the similarity concept.

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Contents of Lecture

1. Examples of physical modeling experiments
2. Dimensions of fluid mechanics properties
3. Dimensional Analysis of Bernoulli's Equation
4. Concept of Similarity or Similitude
5. Solved Examples
6. Summary

Now if you talk about that I will start with the physical modelling experiments, what we have in IIT Guwahati or elsewhere, how we conduct the physical modelling experiment. Then I will talk about the dimensions of fluid mechanics properties which last class we discussed, but just I have to repeat it and more interesting things today I will talk about the dimensional analysis of Bernoulli's equation okay.

Then I will talk about the concept of similarity or similitude, solved examples and summary. Let us look at very interesting study.

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Applications

Scaled model of Brahmaputra river braided loop in Laboratory flume IIT Guwahati

Braided loop in Brahmaputra river



| Parameter | Prototype | Model |
|---------------------------------|----------------------------|----------|
| Particle size (d _s) | 4.21 mm | 0.21 mm |
| Discharge | 30,000 m ³ /sec | 10 l/min |
| Length of Island | 6 km | 1.73 m |
| Width of Island | 2.5 km | 0.72 m |
| Width of the Right Channel | 4.7 km | 0.18 m |
| Width of the Left Channel | 8.35 km | 0.18 m |

Experimental Run



Modelled experiment done in flume at Department of Civil Engineering, IIT Guwahati



Scaled Braided Loop

What we have been doing in the previous lab in IIT Guwahati. So one sites of the figures if you look at this Brahmaputra river, it is big river systems which have the dimensions in terms of the length of the island 6 kilometre, width of the island 2.5 kilometre. So huge dimensions in terms of the length and the width of the islands, the discharge is about 10,000 metre cube per second, huge discharge, the particle size.

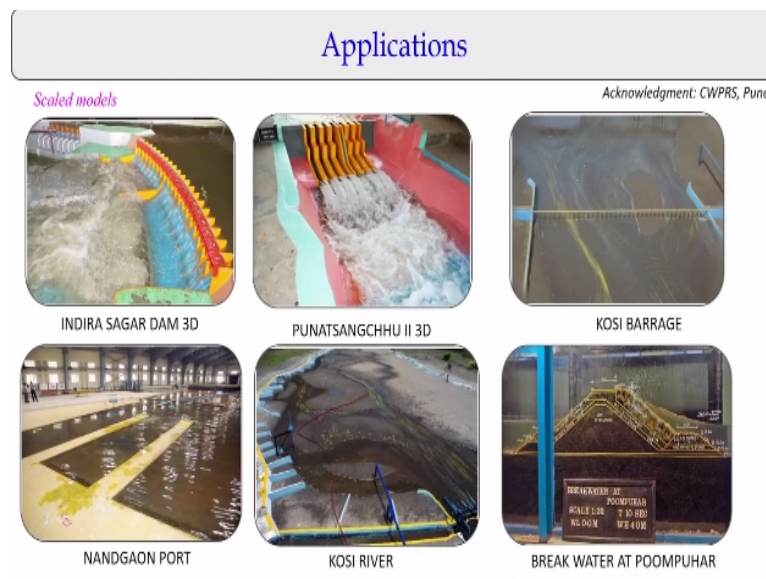
Then width of the left channel and the right channel, these are the dimensions of real rivers and we call the dimensions of prototype. So the real river dimensions what is that is given as a prototype dimensions, that is what we reflect in the modelling setups what we have, where we scale down it with the distance level as well as the geometry level we scale down it, like for example, the length of the island at the prototype level is 6.5 kilometres.

But the dimensions what you have put it here is about 1.73 metres. So that is what is called geometric similarity. So we scaled down the models with an appropriate scale. Similar way

also we have scaled down the discharge which is at the prototype level it is 10,000 metre cube per second, but at the models or at the prove levels we tested with a discharge of 10 litre per seconds.

So how to do this type of calculations what could be the model discharge so that it can represent the flow behaviours at the prototype levels. This is a biggest question what today will be answered and if you look at these 2 figures you can see these are the 2 experimental data or experimental geometries of this river represented for the Brahmaputra rivers.

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Same way if you look at that there are series of physical models conducted in CWPRS, Pune. So like the Kosi barrage if you know it the Kosi barrage, this is the physical models of the Kosi barrage, which is the scale down the physical model of Kosi barrage. Similar way Indira Sagar Dam 3D models if you can look it which is a scale down models here. Same way the Nandaon port, Kosi river barrage, break water at Poompunhar and 3D models of this ones.

If you look at these models there are the scale down models from the prototypes, but when you do these also we try to look other similarities, what are they? That is what today we will discuss it, but these type of experimental set up we conduct before implementing major projects like barrage, the dam projects, the port projects, all the major project before implementing it these all we tested.

And tried to find out what could be the optimum solutions for these Kosi barrage as well as the Kosi river projects. Like for example, if you can see it there are the flow lines are there,

you can see these flow lines. You can see here there is energy dissipation is happening, you just see it, where you can see it, if you conduct a physical model you can really just observe the flow patterns.

You can see this flow patterns, how the flow is going on. It is very easy to observe the flow pattern, the stream lines, the vortex formations all we can see it very closely conducting this experiment. Similar way if you are looking it how much of energy dissipated just downstream of the spin wheel or the fluids gates you can easily find out how these, the eddies and the vortex, the energy dissipations what is happening.

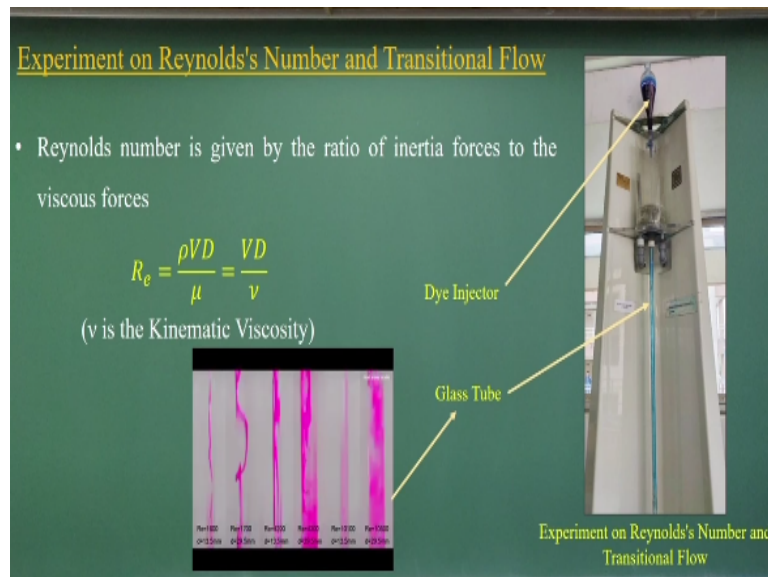
And after that how the hydraulic jump or missions are happening, all these things we can study when you conduct series of physical models. Most of the civil engineering projects before implementing the field, we conduct a series of physical modelling test also we conduct numerical models what available today in different commercially or free softwares we also conduct the experiment.

But I can say that most of the times we relay, we depend upon the physical model because that what gives a lot of the strength the support to engineer to take the decision because they can see visually how the flow (()) (07:21) happening it, like for example, of the Kosi barrage, if you look into the flow patterns, all the things we can visualize it with a different flow conditions.

So consider this visualisations part considering the flow patterns to observe even if in a scale down models that is what gives a lot of confidence to the engineers before implementing. So I can say there is a 2 complementing each other. The computational fluid dynamics and the scale models they are complimenting each others. We cannot construct a barrage or the dam without conducting physical models.

So both are complementing each other in terms of understanding what will be the flow (()) (08:13) what will be the energy dissipation all we can understand conducting series of physical models. Now you can have the questions in your mind then apart from the geometric similarity what you can see it always a scale models have a scale down model and sometimes also use a scale of models that means always tell it a 1:10 or 1:100, the scale down models.

That means 1 unit of the models representing 10 unit of prototypes or 1 unit of models representing 100 units of in the prototypes. So we do the scale down models to represent the things also sometimes we also go for scale of models. The models are bigger size than the prototype, but these are very special scales. So of you look at this way we have a lot of applications of the physical models conducted or any major river projects or the dam projects. **(Refer Slide Time: 09:29)**



Now if you look it before starting the topic on similarities, I can say that let us have do a small experiments which is called Reynolds number apparatus experiment which is very simple experiment what was conducted by Reynolds with a colour dye facilities, is a dye injectors and there is a pipe which is regulated the floor here and the flow can be conducted with different Reynolds numbers, the flow Reynolds numbers.

The flow Reynolds number as you know it is defined as this way, that means inertia force by viscous force, if I make it that receives will gives Reynolds number, but this that what as you increase the number of the Reynolds numbers as is indicated this that, if you increase the number of Reynolds number you can see this coloured dyes are changing it, that means there are lot of diffusions of coloured dyes happening.

The flow patterns are changing it, visually what we are saying it, there is change of the flow patterns, there is change of flow from the laminar to transitions to the turbulent. We will discuss all how it happens with virtual fluid ball concepts but you can see that with simple coloured dye experiments we can find out at what the Reynolds numbers, the flow changes from lamina to transitions.

The transitions stage to the turbulent stage, we can identify and we conduct the experiment with respect to the nondimensional number of Reynolds numbers. So that way this is a very simple experiment to find out the threshold of the Reynolds numbers to divide between laminar transitional flow, transitional flow and the turbulent flow. So more details we will discuss in the next class.

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| Dimensions of Fluid Mechanics Properties | |
|--|---------------------|
| • Length | $M^0 L^1 T^0$ |
| • Area | $M^0 L^2 T^0$ |
| • Volume | $M^0 L^3 T^0$ |
| • Velocity (speed) | $M^0 L^1 T^{-1}$ |
| • Acceleration | $M^0 L^1 T^{-2}$ |
| • Volume flow (Discharge) | $M^0 L^3 T^{-1}$ |
| • Kinematic viscosity | $M^0 L^2 T^{-1}$ |
| • Strain rate | $M^0 L^0 T^{-1}$ |
| • Pressure, stress | $M^1 L^{-1} T^{-2}$ |
| • Viscosity | $M^1 L^{-1} T^{-1}$ |
| • Force | $M^1 L^1 T^{-2}$ |
| • Moment flux, Torque | $M^1 L^2 T^{-2}$ |
| • Power | $M^1 L^2 T^{-3}$ |
| • Work, Energy | $M^1 L^2 T^{-2}$ |
| • Specific weight | $M^1 L^2 T^{-2}$ |
| • Mass flux | $M^1 L^0 T^{-1}$ |
| • Surface tension | $M^1 L^0 T^{-2}$ |
| • Density | $M^1 L^{-3} T^0$ |

Now let us coming to the dimensions of the fluid mechanics properties, as discussed in the last class, I am just repeating it that you have the dimensions of basic geometry which in terms of length, area, volume. Then comes out the velocity, accelerations and volumetric discharge that means volume per unit time, that is what the discharge, volumetric discharge, volumetric rate.

Kinematic viscosity and the strain rate, similar way we look it this sides, the dimensions of a pressure, stress, viscosity, momentum flux and torque, power, work and energy, mass flux, this is the momentum flux, this is for the mass flux surface tension and the density. So I am not repeating these, but just to have the, showing you the dimensions of basic fluid properties, what we generally encounter to solve the problems.

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Dimension Analysis of Bernoulli's Equations

- Bernoulli's equation derivation.

Conservation of mass for considered elemental control volume yields

$$\frac{d}{dt} \left(\int_{cv} \rho dV \right) + \dot{m}_{out} - \dot{m}_{in} = 0 \approx \frac{\partial \rho}{\partial t} dV + d\dot{m} \quad \left[\begin{array}{l} \dot{m} = \rho AV \\ dV \approx A ds \end{array} \right] \quad d\dot{m} = d(\rho AV) = -\frac{\partial \rho}{\partial t} A ds$$

$$\left[\frac{1}{T} \left(\frac{M}{L^3} \right) (L^3) \right] \left[\left(\frac{M}{L^3} \right) (L^2) \left(\frac{L}{T} \right) \right] \longrightarrow \left[\left(\frac{M}{T} \right) \right]$$

Linear momentum relation in the streamwise direction

$$\sum dF_s = \underbrace{-\gamma A dz}_{\text{Gravity force}} - \underbrace{A dp}_{\text{Pressure force}} = \frac{\partial}{\partial t} (\rho V) A ds + d(\dot{m} V)$$

$$\left[\left(\frac{M L}{L^2 T^2} \right) (L^2) (L) \right] \left[\left(\frac{M}{L T^2} \right) (L) \right] = \left[\frac{1}{T} \left(\frac{M}{L^3} \right) \left(\frac{L}{T} \right) (L^2) (L) \right] \left[\left(\frac{M}{L^3} \right) (L^2) \left(\frac{L}{T} \right) \left(\frac{L}{T} \right) \right] \longrightarrow \left[\left(\frac{M L}{T^2} \right) \right]$$

Now if you look it, many of the times when we derive a big equations, we face a difficulty or we face have a doubt over that, the equations whatever I have derive it are they correct? In a equation you can have soft components, are the soft components are correct? So what do we do it, we use a dimensional analysis concept to find out the equations what we have derived is it correct, also we can look at the equation derivation at the step by step that what is the unit.

Or what is the dimensions of each term of equations, if you evaluate that then you can check it the correctness of the equations. That is what if you look at this equations, this looks very complex, okay. There is a equations which is involved with volumetricals and divide it there is a mass flux in and mass flux out, it looks like very difficult equations. It is having that stands that we will do mistakes in any of the part of the equations.

What you do it that case, that you just check the correctness of this equations, substitute the dimensions of each terms like rho dv, dv is the volume stands for, 1 by T is the time, d by dt is 1 by T. So you get dimensions of these part. Similar way this is mass flux coming in and going out, that is what VV and by T. So that way if you look it the each terms of this equations having the same dimensions that means the equation is correct.

The same way you can try it look this ones, this also will have a same expressions. So we can always look it whenever you have a doubt, over a equations which is mostly the lengthy equations you substitute the dimensions and see that each term of the equations whether have the same dimension or not. If not, then you check it where it is the mistakes. So that is what in this case, the conservation of mass which look is very complicated equations.

But to know the correctness of the equations we use the dimensions of each term then find out what is the dimension of each term then the part what we look it at the dimensionally homogeneous, that is what we tested it. Similar way this if you look at the linear momentum relation in the streamwise direction which looks very difficult equations what we have, we write it from these, the sum of force is gravity force and pressure force, again we write in this form.

If you look it there is a differences, so all these terms if I substitute the one by one the dimensions like in this case gravity force, this is the unit weight, area, then dz, this is a area dp, the pressures. Similar way if I substitute all the terms if you look at that each terms having dimensions into L by T square which is the force. So each terms are equating into the force.

So these concept what I introduce for you only whenever you derive a big equations, complicated equations like there will be a integral part, differences part, please use the dimensional analysis compound to find out are they correct in terms of concept of dimensional homogenous of this equation. Most of the physical equations are dimensionally homogeneous.

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Dimension Analysis of Bernoulli's Equations

- Bernoulli's equation derivation.

Bernoulli's equation for unsteady frictionless flow along a streamline

$$\frac{\partial V}{\partial t} ds + \frac{\partial p}{\rho} + V dV + g dz = 0 \quad \longrightarrow \quad \int_1^2 \frac{\partial V}{\partial t} ds + \int_1^2 \frac{\partial p}{\rho} + \frac{1}{2}(V_2^2 - V_1^2) + g(z_2 - z_1) = 0$$

$$\left[\frac{1}{T} \left(\frac{L}{T} \right) (L) \right] + \left[\frac{L^3}{M} \left(\frac{M}{LT^2} \right) \right] + \left[\left(\frac{L}{T} \right) \left(\frac{L}{T} \right) \right] + \left[\left(\frac{L}{T^2} \right) (L) \right] \quad \longrightarrow \quad \left[\left(\frac{L}{T^2} \right) (L) \right]$$

For steady incompressible flow

$$\frac{p_1}{\rho g} + \frac{1}{2g} V_1^2 + z_1 = \frac{p_2}{\rho g} + \frac{1}{2g} V_2^2 + z_2 = \text{const}$$

$$\left[\frac{M}{L T^2} \right] + \left[\frac{L^3}{T^2} \right] + [L] \quad \longrightarrow \quad [L]$$

Now the similar way you know it is most often what we do in the fluid mechanics, we use the Bernoulli's equations, okay, mostly widely used or widely misused equations, which is called the Bernoulli's equation. We discussed lot about this equations. So let us have again look at

that in a dimensional analysis of Bernoulli's equations with a derivations part. If you look at the unsteady frictionless flow along a streamline which is the Bernoulli's equations, it look it in terms of differences, the integrations part and all the things substitute the dimensions.

Finally, we will see it the each terms having the same dimensions L square by T square. Substitute that, I just encouraged the students have these practise, wherever you derive the equations, just spends few minutes to write the dimensions of these variables, each term, then check it whether it is dimensional homogenous. So that way you can use each dimensions and check it this is what.

The similar way you can check this equations also. If there is a mistake in this equations you can easily identify when you equate the dimension of each terms, because it is dimensional homogeneous equations. So each term should have the same dimensions and if you equate it you will get same thing. So if you go for a simple model this is what called a very, it is not a complex that merge, but we can say that having integrations and all the fact.

So but when you talk about a steady and compress flow, you know the standard Bernoulli's equation in a different forms and you just substitute it, you will get the dimensions which is the length dimensions. So we always use the dimensions to understand it whether is there is a correctness of the equations, if not then we look it where is the mistakes. Not only that you can also interpret it each term what is representing it.

Like for example, what I have here is the length, that means it is an edge equivalent to a water head. It is a length dimension, it is L equal to energy in terms of water head, that is what we are getting it here. So the dimensions also speaks out that what type of conservations we are doing it, but we can also interpret it the physical meaning of this dimensions what we are getting it.

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Similarity (Similitude)

- In fluid dynamics similarity is usually the relation between a full-scale flow and a flow with smaller ones.
- Similarity concept is use for model testing.
- Instead of complete similarity, in engineering it uses particular types of similarity.
- The most common types of similarities are
 - Geometric similarity
 - Kinematic similarity
 - Dynamic similarity
 - Thermal similarity

So looking that part, let us go for the next step which is the similarity or similitude (()) (20:13) that means in fluid dynamics when you conduct the experiments, we should have a relationship between full scale or the prototype and the flow with smaller ones which is the model. We need to have a relationship between that. That relationship if you can use it by conducting the experiment at the model scale you can take it to the prototype scale.

If that is the conditions either you conduct the experiment with the full scale as we saw lot of experiment facilities for automobile industry they do, to tell full scale models okay, but many of the cases we cannot go for the full scale models like a dam which is in generally of having the dimensions for 30 meters high, it is width of 40 meters, more than that, we cannot conduct these type of big experiment scale experiment in any big set up.

So we cannot do a full scale models for a dam, full scale model for the barrage, but we can conduct full scale models for automobile aerospace industry problems also, but not in the problems which we encounter in civil engineering problems, which have more dimensions we scaled down the models which we do the scale down of the models we have to look the similarity.

This 4 type of the similarities happens geometric similarity, kinematic similarity, dynamic similarity and the thermal similarity. So as we are not talking about energy, conservations much more in these lectures, we focus on these 3 similarity, geometry, kinematics and the dynamic similarity.

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Geometric Similarity

- A model and prototype are geometrically similar if and only if all body dimensions in all three coordinates have the same linear scale ratio.
- The geometric similarity requires that all homologous points be related by the same linear scale ratio.
- This applies to the fluid geometry as well as the model geometry.
- All angles, flow directions are preserved and the orientations of model and prototype with respect to the surroundings must be identical.

Boeing phantom works X48B

Models

*Source: NASA

So if we look in that part, the first I am talking about geometric similarity. If you look it, this is what the prototypes, pole scale okay, that is what is the Boeing X48B but we cannot conduct this big scale experiments, what we do it we scale down it. We make it exactly the same in terms of a scale down models so that we keep all the angle, the flow direction are preserved.

Orientations models and prototype with respect to surrounding must be identical. So what we do it we do a geometrical similarity with a same linear scale ratio. Same liner scale ratio we apply it and make it to geometrically the similarity that is what is the geometrical and similarity models what exactly you can compare visually that they are geometrical scale down it.

They are like the length, the area, the volume, all geometric scale down with the angles and all this and finally, we testing in the wind tunnel facility, that is what the wind tunnel facilities this model is tested in the wind tunnel facility and whatever the pressure variations, the velocity variations, they we take it from the model to the prototype to design a robust Boeing fighter plane. So this is what have been doing it with the geometric similarity.

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Kinematic Similarity

- The motions of two systems are kinematically similar if homologous particles lie at homologous points at homologous times.
- It depends on time scale along with length scale.
 - Reynolds number similarity
 - Froude number similarity
 - Mach number similarity

No free surface flow prototype

No free surface flow model

But we also to look it should have a kinematic similarity. When you talk about the kinematics what it says that we have the model, we have the prototypes, that this is the prototypes, this is the models, that means in the model and prototypes would have the same velocity factor, the stream lines patterns that means the velocity factors what we have the velocity direction that stream line and the models would have a scale factors okay.

We can have a scale factor so that the kinematic similar is a homologous points, the points what we have to telling it which is the representing models and the prototypes that should have a lies at the homologous points at the homologous times and same time in time and also in a positions, this would have the same location, same factors, so we will represent it. If it is that then it is called the kinematics similarities.

So it depends of the time scale along with the length scale. So 2 scales are there. The time scale and the length scale. So to achieve this we do a Reynolds number similarity, Froude number similarity or Mach number similarity.

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Kinematic Similarity

- Frictionless flows with a free surface are kinematically similar if their Froude numbers are equal.

$$Fr_m = \frac{V_m^2}{gL_m} = \frac{V_p^2}{gL_p} = Fr_p$$

- Froude number contains only length and time dimensions, it is purely kinematic parameter that fixes the relation between time and length.

$$L_m = \alpha L_p$$

$$\frac{V_m}{V_p} = \left(\frac{L_m}{L_p}\right)^{1/2} = \sqrt{\alpha} \quad \frac{T_m}{T_p} = \frac{L_m/V_m}{L_p/V_p} = \sqrt{\alpha}$$

Free surface flow prototype waves

λ_p
 H_p
 V_p
 $Period = T_p$

Free surface flow model waves

$\lambda_m = \alpha \lambda_p$
 $H_m = \alpha H_p$
 $V_m = V_p \sqrt{\alpha}$
 $Period = T_p \sqrt{\alpha}$

Now if you look at another problem where we are looking for the similarity length, like for example, we are looking for a free surface flow with a prototype waves. This is the wave process maybe happening in oceans or the lake that what we have to represent it in model waves. When you do that if you look at that the way we have characteristics like the height of the wave, the length of the wave and also we have the velocity factors.

In these case since it is a free surface flow conditions, flow Froude numbers should be equal or model as well as for the prototype, that is what is there, the flow Froude numbers of the model and prototype should be equal then we are substituting the flow Froude numbers in terms of the velocity and the length. Since we are conducting the experiment on the R surface so G does not vary, the acceleration due to gravity does not vary.

So you can use the same G components, so you can get it the a relationship between the velocity at the model, length velocity of the model and the velocity and the length of the prototypes there is a relationship what we get it when you do kinematic similarity, that means equating flow Froude numbers or model is equal to flow Froude number of the prototype.

So if you look at the scales, so the flow Froude numbers contains the length and the time dimensions because there is no mass dimensions in that. So it is purely kinematic parameters fixes the relation between length and time scale. If I consider the alpha scaling factors between the prototypes and the models if I use this relationship, I can get the what could be the ratio of the velocity of the models and the velocity of prototypes with substituting this equations will be square root of the alpha.

Similar way the time scale will be computed as like this, so these are very simple calculations can be done. So if you look at that way, this is what the prototype scale after the scaling down the same process with scale down the length in terms of alpha factors which is the length of the wave and the height of the waves but the velocity and the time will have a different scale factors. This is what we computed based on flow Froude number similarity concept.

So this is what the time ratio or time scale and the velocity scale as make it, so most of the times we do these things to compute it what could be the if this is the length scale what could be the time scale, what could be the velocity scales, so that we can represent the flow which is kinematic similarity between prototypes and the model.

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Dynamic Similarity

- It exists when the model and the prototype have the same length, time scale and force scale ratios.
- Initially Geometric similarity must required for the dynamic similarity.
- Dynamic similarity exist along with kinematic similarity, if the model and prototype force and pressure coefficients are identical.

$$F_i = F_p + F_g + F_f$$

Inertia force
Pressure force
Gravity force
Friction force

- For compressible flow: Reynolds number, Mach number and Specific heat ratio.
- For incompressible flow: Reynolds number (no free surface), Reynolds, Froude, Weber, Cavitation numbers etc. (for free surface flow)

Let us discuss about the dynamic similarity, these similarity adjust when you have the 3 scale ratios, like the length, time and the force. So are the same or model and the prototypes. So the dynamic similarity happens not only this length and the time scale but also the force scale similar ratios will be there, what do you mean by that if you have a let you have a problems like this, you have a prototype, you have a gate.

And flow is passing through gate and having the hydraulic jump here with having a small eddies or vortex formations like this. This is the point where we are looking at what are the force components are there as you know it, it will be the pressure force component, gravity force component, friction force or the viscosity force component and inertia force component and each force has the directions component.

If you look at these they should have a balancing all these force, vector balancing components at the prototype level. If prototype and models are at dynamic similarity that means the vector diagrams of this force component of the prototypes and the model should be exactly the same. Force magnitude make the difference but the vector diagrams, vectorical diagrams (()) (30:35) all these component should be exactly same.

So that the force all these component should be exactly same if it is that we can make a ratio between forces of inertia force of the model and the prototype this would be equal. So if you look at these concept when it hold good we call dynamic similarity to achieve the dynamic similarity first you should have geometric similarity as well as the kinematic similarity. If you do not have these 2 similarity, we cannot achieve the dynamic similarity.

So when a dynamic similarity are the same the model prototype force and pressure components are identical that means the ratio look the same. So if you look at this way the force what is acting is here and the if you look at this the diagrams, the force vectorical diagrams of model and prototypes they should have the same. If you exactly know from the vector calculus, we can compute it but will be the ratio between them.

The ratio between them should be equal otherwise the vectorical additions of these exact similar will not be (()) (31:52) you make it the ratios are the same, the directions and the ratios are the same value. Mostly if you look at these for the compressible flow, we use the Reynolds numbers, Mach numbers specific heat ratios but incompressible to without free surface flow conditions we mostly the Reynolds numbers.

But others like numbers also comes, the Reynolds number, Froude number, Weber, Cavitations number what we discuss can be used for free surface flow.

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Relationship between Dimensional Analysis and Similarity

- In fluid dynamics similarity is usually the relation between a full-scale flow and a flow with smaller ones.
- For dynamic similarity rules the forces acting at the points are similar

$$\frac{(inertia\ force)_m}{(inertia\ force)_p} = \frac{(pressure\ force)_m}{(pressure\ force)_p} = \frac{(friction\ force)_m}{(friction\ force)_p} = \text{const.}$$

$$\frac{(inertia\ force)_m}{(friction\ force)_m} = \frac{(inertia\ force)_p}{(friction\ force)_p} = (\text{const.})_1$$

$$\frac{(inertia\ force)_m}{(pressure\ force)_m} = \frac{(inertia\ force)_p}{(pressure\ force)_p} = (\text{const.})_2$$

Now let us derive the relationship between the dimensional analysis and the similarity. As I told from the vector diagrams of the force components that the dynamic similarities force acting these points are similar in these case the inertia force of model and the prototype, pressure force of model and prototype, friction force are the viscous flow model prototype should be constant.

Then dynamic similarity it is achieved and that is the case so now we can just reshuffle these equations to get it at the model level and the prototype level we get a one constant. Similar way we write inertia force and the pressure force, inertia force we get another constant. So you are equating as I said it earlier we equate the flow Froude number similarity with in case of free surface flow.

So similar way we can establish these equations this is the Reynolds number equation that this is what the Euler equations part, what we can get it by equating this part.

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Relationship between Dimensional Analysis and Similarity

Friction force computation

- Force due to the viscosity (friction) is $\frac{\partial \tau}{\partial n} dndsdz$
- The shear force can be expressed as $\mu \left(\frac{\partial^2 |V|}{\partial n^2} \right) dV$
 $dV = dndsdz$

Pressure force computation

- The net pressure force $\left(\frac{\partial p}{\partial n} \right) dV$

Inertia force computation

- For steady flow
 $dma_T = (\rho dV) |V| \frac{\partial |V|}{\partial s}$

Now just to look it, I am not going detail derivations of this part if you take a fluid element along a stimuli like this is the fluid element okay, this is the stream line which is having dx and dn dimensions, you have the shear stress which is changing at this along the n'th directions and you get it what could be the shear stress. Similar way you can find out the pressure values and all.

Then you can compute the force due to the viscosity that will be the change of shear stress into the volumetric part. That is what if you portrait you get it this part. Rest you substitute the Newton's laws of viscosities and all, then you will get this part. Similar way the net pressure force acting of this you can see it will be this part and inertia force computation which is the, in case of the steady flow, mass into the acceleration or rate of change of the momentum flux that is what the mass and the momentum flux but you compute it, that along the stimuli directions will give us the inertia force components.

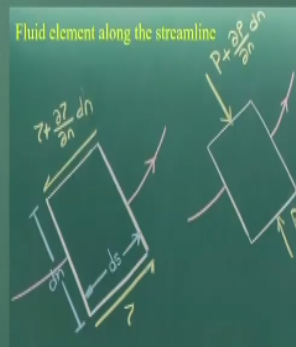
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Relationship between Dimensional Analysis and Similarity

- The laws of dynamic similarity the ratio of the forces expressed as

$$\left[\frac{\rho |V| \frac{\partial |V|}{\partial s}}{\mu \frac{\partial^2 |V|}{\partial n^2}} \right]_m = \left[\frac{\rho |V| \frac{\partial |V|}{\partial s}}{\mu \frac{\partial^2 |V|}{\partial n^2}} \right]_p$$

$$\left[\frac{\rho |V| \frac{\partial |V|}{\partial s}}{\frac{\partial p}{\partial n}} \right]_m = \left[\frac{\rho |V| \frac{\partial |V|}{\partial s}}{\frac{\partial p}{\partial n}} \right]_p$$



If you equate it and substitute these values in case of loss of dynamic similarities the ratio between these parts, you can see that these equations come out to be the Reynolds number and this equation comes out to be the Euler number. So basically we are trying to tell it that when you go to the element level we can derive the ratio between inertia force to viscous force which comes out to be Reynolds numbers.

We can compute it and you have the same expressions. Similar way if you are computing the ratio between inertia force to the Euler number which will be the reverse of the Euler number that what also we will get it and we will get the expressions of the Euler number and the Reynolds number. So it is quite easy, you can look at the stream line at the element level as well as the gross characteristic levels we can understand the flow reverse in terms of Reynolds number similarity or the Euler number similarity.

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Example 1

Testing of an automobile vehicle in the Wind Tunnel to find the aerodynamic drag and power required to overcome this drag

Given Data

Model width : 2.44 m
Frontal Area : 7.8 m²
Testing Velocity : 100 km/h
Scale : 16:1
Drag Coefficient : 0.46

To determine the power required for prototype

Parameters

At standard sea level: p=101325 Pa, T=288 K

$$\rho = \frac{p}{RT} = 1.226 \text{ kg/m}^3$$

$$\mu = 1.46 \times 10^{-6} \frac{T^{3/2}}{T + 111} \\ = 1.79 \times 10^{-3} \text{ kg/m.s}$$

Now let us come back to examples like this, let us have a testing of automobiles in a wind tunnel to find the aerodynamic drags, the power required to overcome this drag part. The data is what is given is model width frontal area, testing velocity, the scale, drag coefficient. It is given these data, we need to compute the power required for the prototype level. So since the pressure, the temperatures are given at the standard levels you can find out what will be the density of the air.

You can find out what will be the dynamic viscosity of air which the functions of the temperature, you can compute it this way.

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| Step 1 | Step 2 |
|---|--|
| Model Width, $w_m = \frac{w_p}{16} = \frac{2.44}{16} = 0.153 \text{ m}$ | Reynolds Number for model, $(Re)_m = 46.4 \times 10^5$ |
| Model Frontal Area, $A_m = \frac{A_p}{16^2} = \frac{7.8}{16^2} = 0.0305 \text{ m}^2$ | Drag for the prototype: |
| For dynamic similarity: | $D_p = C_D \frac{1}{2} \rho V_p^2 A_p$ $= 1697 \text{ N}$ |
| $\left(\frac{\rho VL}{\mu}\right)_m = \left(\frac{\rho VL}{\mu}\right)_p$ | Power to overcome this Drag = $D_p V_p$ $= 1697 \times \frac{100}{3.6}$ $= 47139 \text{ W}$ $= 47.139 \text{ kW}$ |
| $(VL)_m = (VL)_p$ | |
| $V_m = \left(\frac{100}{3.6}\right) \times \left(\frac{16}{1}\right) = 444.4 \text{ m/s}$ | |

Now you can have the model width and there is a scale ratio is the given for the model width. We can compute it with the width what could be the dimensions here, the model frontal area,

since the length is 1 by 16, the scale is (1/16) (37:07) and area will have a L square that mean 1 by 16, 1 by 16 so we use for the area 1 by 16 square to compute it with the model frontal area. We use the dynamic similarities means the Reynolds numbers of the models should equal to the Reynolds numbers of the prototypes since the density and the mu.

The same air we are using it so density and the mu are the same so it is come down with this value. So substituting these we can find out what could be the model velocity. Then we can compute it what will be required the Reynolds numbers for the models, because we know the velocity, we can find out what will be Reynolds numbers and what will be the drag force of the prototypes also we can compute it and power requirement of the overcome this drag force also we can compute it using the power is equal to the force into velocity component.

That is what you can use it to compute this part, it is very easy just you have to have a, the many equations is to use is your very simple equations and you have to compute it okay. So like for example, is that we do not know what is the equations of this, you just put the dimensions and check it that whether it is a force component, CD does not have the dimensions, the p square the rho and Fe you just substitute it you will get it the force, the dimensions. Similarly, the power is energy per unit time, you can use this force in to the velocity will be the power.

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Example 2

Problem type: Flow over a sphere [GATE 2017]

Given Data

Type of flow : Laminar flow
Drag Coefficient : $C_F = \frac{F}{\rho V^2 D^2}$

Density (ρ) = 1000 kg/m³
Diameter of Sphere (D) = 100 mm
Velocity (V) = 2 m/s
CF = 0.5

If water now flows over a another sphere of 200 mm diameter, under DYNAMICALLY SIMILAR conditions, Compute the drag fore on sphere 2

Let us come to the second problem which is flow over a sphere which is GATE 2017 questions which is given laminar flow, drag coefficient equations, the density, diameter of the sphere is given, velocity and the CF value is given. Then water now flows over a sphere of

200 millimetre diameter under the dynamically similar conditions to compute the drag force on the sphere 2.

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Solution

For dynamically similar conditions

$$Re_1 = Re_2$$

$$\left[\frac{\rho V D}{\mu} \right]_1 = \left[\frac{\rho V D}{\mu} \right]_2$$

$V_1 D_1 = V_2 D_2$ ----- Eqn. 1 [ρ, μ are not variables]

We know, $C_F = f(Re)$
 and, $C_{F1} = C_{F2}$ ----- Eqn. 2

Force on sphere 2, $F_2 = C_{F2} \rho V_2^2 D_2^2 = C_{F1} \rho V_1^2 D_1^2$ [From Eqn's 1 and 2]

Solving, $F_2 = 20 \text{ N}$

If that is the conditions what will be the this case, there is no free surface, only the pro Reynolds number of model and prototypes we equate it. As it is not given much details about these 2 parameters the density and the mu you can have a basic equations of this ones, just equating them and you can have a this model and the prototypes you have the same CF value. If it is that is the conditions, you can easily compute it force and put the active value.

So only you have to try to understand it what should be the dynamic similarity will be there, whether the flow, Reynolds number or the flow Froude numbers. Then you will look it at the force levels what is the dynamic similarity conditions like CF1 is equal to the CF2 which is the functions of the Reynolds numbers. So we can find out the what could be the force acting on this.

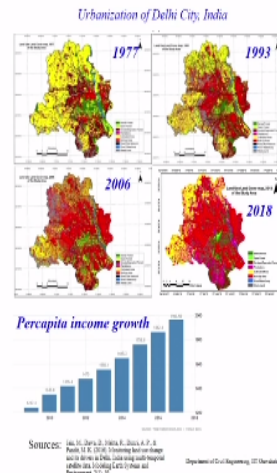
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Economic Model of a Developing City

- Deformable control volume (horizontal and vertical dimension).
- Mass conservation (Money, Job) - inflow/outflow
- Transport process

| | | |
|--|--|--|
| <p>Microscopic</p> <p>Individual level</p> <p>Lagrangian frame</p> | | <p>Macroscopic</p> <p>Bank level</p> <p>Eulerian frame</p> |
|--|--|--|

- Understanding fluid mechanics helps in development of appropriate economic model



Now let us come back before concluding lectures that most of the time we would feel boring of the fluid mechanics (()) (40:35) lot okay but many of the times the knowledge of the fluid mechanics help us to understand so complex problems like economic model of a developing city. We can use our knowledge of fluid mechanics to develop a economy models for a developing city like Delhi.

If you look at this the red colours are the urban areas, these are real datas which is prepared by my students you can see the 1977 what is the red colour area, 1993, 2006, 2018 and this is the real data of economic growth, but we do not know what is going to happen in 2050, 2100, that is what is the economy model students predicted. To do that let us use our fluid mechanics knowledge.

What type of control volume we have, we have deformable control volumes as the control volumes are changing it if you can look it that is control volumes are changing it, both in horizontal and the vertical dimension. Here there are lot of flow is coming, it is mass conservations we follow it either for money or job, the storage and all, there are lot of transport process happened in economy models okay.

In microscopic level and macroscopic level, the knowledge what we have the fluid mechanics the particles movement, the element movement all these things also used to develop economy model. Similar way we look it, whether a Lagrangian or the Eulerian frame works. Eulerian frame works means we talk about at the bank level, they do not look it individual money, they look t gross, a particular bank is locating what is the total turn overs.

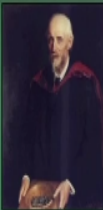



Representing a, so they do not look it the individual part, but individual level a persons is Lagrangian frame work, so that way if you look it if you really understand the fluid mechanics you can solve or you can develop economy models for a developing city like Delhi. So please do have a lot of interest on the fluid mechanics, is not that it is developed just like a the science has developed such a way that with combinations of experiment, theoretical derivations.

The computational techniques, it has come to certain levels that it can also apply many of the fields and most of the fields at the similar concept we follow it and that is what my example to show it. If you are good mathematicians or good fluid mechanic specialist, you can also use the concept of the fluid mechanics to develop a economy models and predict what could be the scenario of the economy or what could be the spread area this red colour area for Delhi city for 2050 or 2100.

With this let us conclude this lecture, but just trying to show it if you look at the history of the pipe flow experiment.

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History of Pipe Flow Experiments

| | | | |
|--|--|--|---|
|  Osborne Reynolds, 1883 $Re = \frac{vD}{\nu}$ |  Poiseuille (1841) and Hagen (1839) $h_1 = 64v \frac{L}{D^2} \frac{V}{2gD}$ |  Julius Weisbach, 1845 $h_1 = \frac{fv^2}{2gd}$ |  Theodor Von Karman, 1930 For rough pipes at high Re $\frac{1}{\sqrt{f}} = 1.14 - 2\log\left(\frac{\epsilon}{D}\right)$ |
|--|--|--|---|

Which started in 1883 with Reynolds Osbourne, Poiseuille and Hagen okay then Julius Weisbach, 1845 and Von Karman in 1930. So each one they have contributed for pipe flow experiment so uniquely to derive this equations and which we so openly today we are using it and for designing the pipe flows. We will have more discussion of these in the next class. Let me thank you for this lecture today.

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