Convective Heat and Mass Transfer

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Module No.# 01
Lecture No. # 01

Introduction to Connective Heat and Mass Transfer

Today, we will begin the first introductory lecture on our course, Convective Heat and Mass Transfer.

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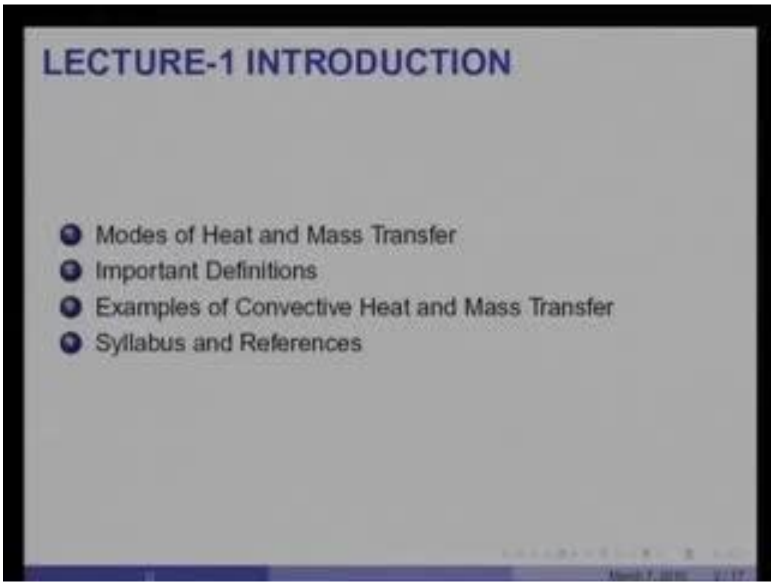

LECTURE-1 INTRODUCTION

- Modes of Heat and Mass Transfer
- Important Definitions
- Examples of Convective Heat and Mass Transfer
- Syllabus and References

In this lecture,I will cover and recall your knowledge of modes of heat and mass transfer, recall some important definitions and give you some examples of convective heat and mass transfer, and then mention syllabus and references.

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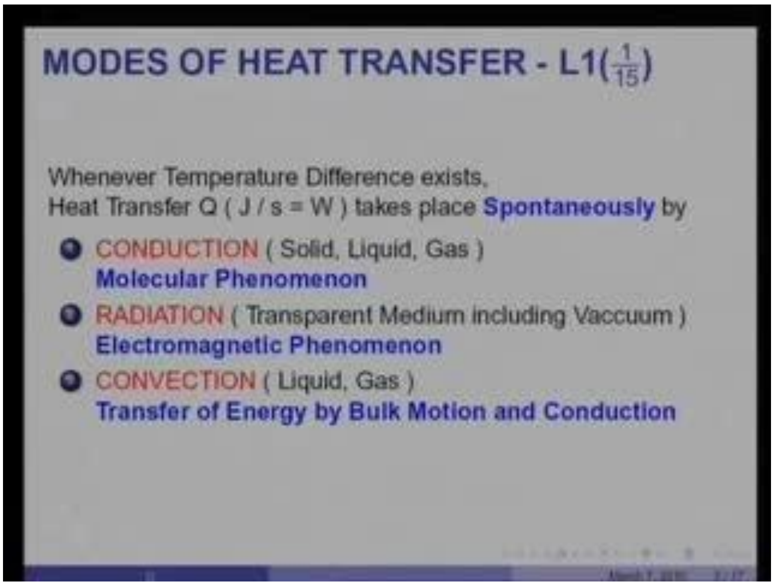

MODES OF HEAT TRANSFER - L1($\frac{1}{15}$)

Whenever Temperature Difference exists,
Heat Transfer Q (J / s = W) takes place **Spontaneously** by

- CONDUCTION (Solid, Liquid, Gas)
  Molecular Phenomenon
- RADIATION (Transparent Medium including Vaccuum)
  Electromagnetic Phenomenon
- CONVECTION (Liquid, Gas)
  Transfer of Energy by Bulk Motion and Conduction

As you all know, whenever there is a temperature difference,heat transfer Q Joules per second or Watts takes place spontaneously by 3 modes:the first of it is the conduction mode and it takes place in solids, liquids and gases;it is essentially a molecular phenomenon.The second mode is radiation;it requires existence of a transparent medium including vacuum.It is anelectromagnetic phenomenon.Convection on the other hand takes place in liquids and gases.In this, the transfer of energy is both by bulk motion as well as by conduction.

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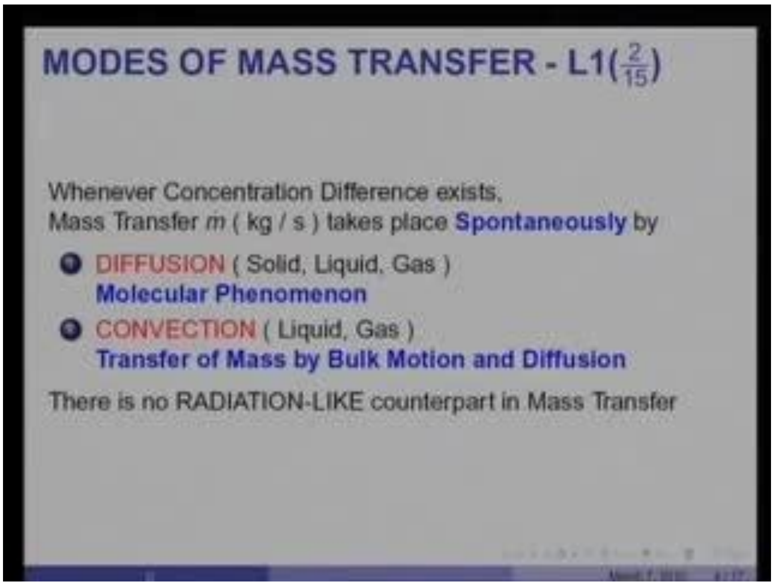

MODES OF MASS TRANSFER - L1($\frac{2}{15}$)

Whenever Concentration Difference exists,
Mass Transfer m (kg / s) takes place **Spontaneously** by

- DIFFUSION (Solid, Liquid, Gas)
  Molecular Phenomenon
- CONVECTION (Liquid, Gas)
  Transfer of Mass by Bulk Motion and Diffusion

There is no RADIATION-LIKE counterpart in Mass Transfer

Likewise, whenever concentration difference exist, mass transfer m dotkilograms per second takes place spontaneously, by firstly diffusion which takes place in solid, liquid and gas.It is a phenomenon very akin to heat conduction; it is also a molecular phenomenon.Likewise convective mass transfer takes place only in liquid and gases in which there is a transfer of mass by bulk motion and diffusion. There is no radiation-like counterpart in mass transfer.

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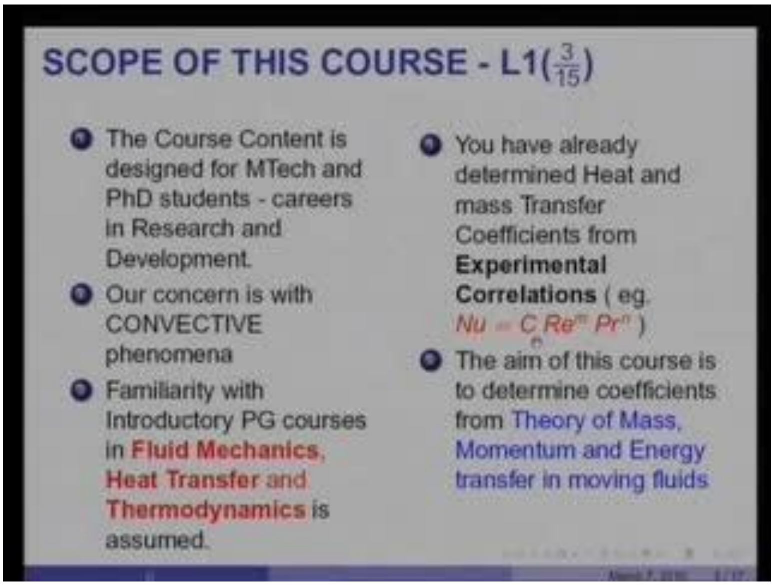

SCOPE OF THIS COURSE - L1($\frac{3}{15}$)

- The Course Content is designed for MTech and PhD students - careers in Research and Development.
- Our concern is with CONVECTIVE phenomena
- Familiarity with Introductory PG courses in **Fluid Mechanics**, **Heat Transfer** and **Thermodynamics** is assumed.
- You have already determined Heat and mass Transfer Coefficients from **Experimental Correlations** (eg. $Nu = C\,Re^m\,Pr^n$)
- The aim of this course is to determine coefficients from Theory of Mass, Momentum and Energy transfer in moving fluids

Very briefly, the scope of this course is as follows:The course content is designed for Masters and PhD students who wish to pursue careers in research and development.

Our concern is with convective phenomena.To the extent that fluid motion is involved, the neighbors of convective heat transfer are fluid mechanics, thermodynamics, and under graduate heat transfer.I shall be assumingthat you have familiarity with these 3 courses. For example, you have already determined heat and mass transfer coefficients from experimental correlation such as Nusselt number is equal to constant multiplied by Reynolds number to the power of m multiplied by Prandtlnumber to the power of n and C m n are specific to a particular situation in which you are considering the heat transfer.

The aim of this course is to determine the heat and mass transfer coefficients from theory of mass, momentum, and energy transfer in moving fluids.Many a times we shall obtain results in close form that will look like experimental correlations.On many other occasions, you will find that we can only give results in tabulated forms which can then be correlated in this experimental like form.

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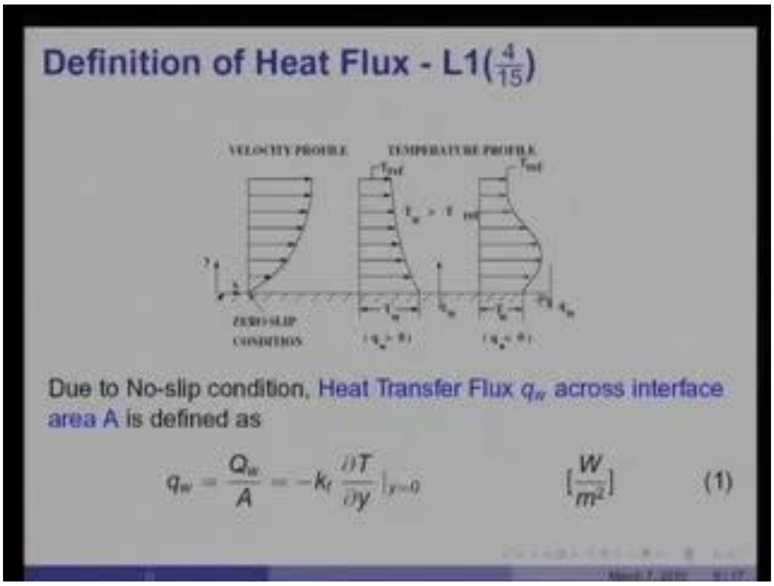

Definition of Heat Flux - L1($\frac{4}{15}$)

Due to No-slip condition, Heat Transfer Flux q_w across interface area A is defined as

$$q_w = \frac{Q_w}{A} = -k_f \frac{\partial T}{\partial y}|_{y=0} \qquad [\frac{W}{m^2}] \qquad (1)$$

The most important quantityin convective heat transfer is the heat flux at the wall; itis shown here.For example, consider a solid surface past which a fluid is flowing.Then, due to action of viscosity close to the wall, the fluid will develop a velocity profile with 0velocity at the wall.This is called the no slip condition; meaning thereby, the fluid does not slip at the surface, but is brought absolutely to rest at the surface.If there was a heat transfer, then the most commonly developed temperature profile will be as shown in this, where there will be some reference temperature far away from the wall and the wall temperature would be greater than fluid temperature.So, the heat transfer would take place that way.

Heat transfer however could also take place in another way.In the sense, although T w here is also greater thanT ref, we shall encounter situations in which the fluid temperature close to the wall is greater than that of the wall, in which case the heat transfer would take place to the wall although the wall temperature is bigger than the free stream temperature. So,I have shown here both the cases of positive heat transfer as well as negative heat transfer.

We define heat transfer flux: suffix q w across interface area A as q suffix w equal to the total heat transfer Q w inJoules per second divided by area.Therefore, it has units of Watts per meter square. Because the fluid is brought to rest at the wall, the heat transfer is actually by conduction.Therefore, we represent it as: By Fourier's law of heat conduction minus k f d T d y at y equal to 0,where k f is the conductivity of the fluid.So, in this case, d T d y is negative.Therefore, the heat flux is positive.In this case, however d T d y is positive.Therefore, the heat transfer is negative or into the surface.

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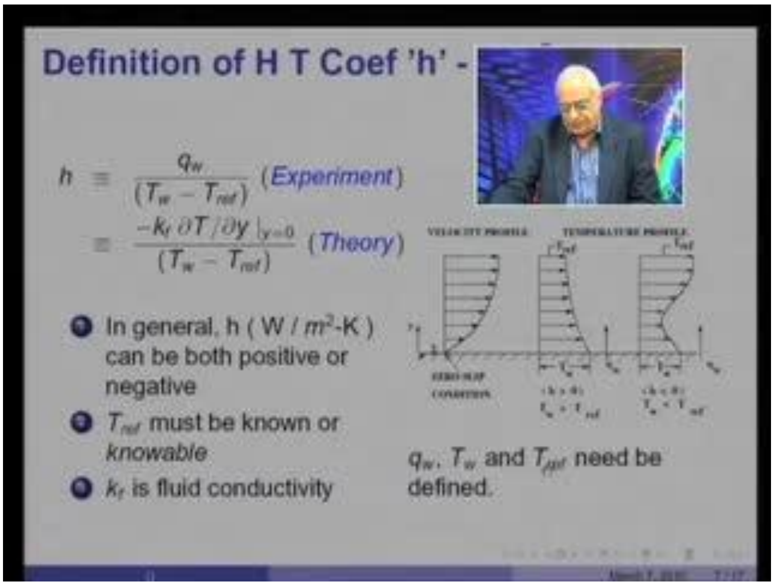

Definition of H T Coef 'h' -

$$h \equiv \frac{q_w}{(T_w - T_{ref})} \text{ (Experiment)}$$

$$\equiv \frac{-k_f \, \partial T / \partial y \,|_{y=0}}{(T_w - T_{ref})} \text{ (Theory)}$$

- In general, h (W / m^2-K) can be both positive or negative
- T_{ref} must be known or *knowable*
- k_f is fluid conductivity

q_w, T_w and T_{ref} need be defined.

We define heat transfer coefficient in the following ways: h is equal to q w divided by T w minus T ref.Since q w is equal to minus k f d T d y at y equal to 0, h can also be defined in this manner.Experimentaliststypically use this definition because q w and T w are easy to measure.

In theory, however we shall be using this definition (Refer Slide Time: 06:37).Theoretical results are compared with experiments.It is very important to remember the difference between the two.Usually, we expect agreement of the order of plus, minus 10 percent in single phase heat transfer. (Refer Slide Time: 06:55) Here I have shown the velocity profile - the most commonly occurring temperature profile for positive heat flux, but we could alsoget situations in which T w is less than T reference.But still, the heat transfer is positive; that is because the temperature profile here has a negative gradient at the wall, and T w is less than T ref.

So, in general, then h can be both positive or negative because, in this case, q w is positive andT w is greater than T ref.Therefore, h would be positive;that is shown here (Refer Slide Time 07:32), but in this case T w is less than T ref, q w is positive, and therefore, h would be less than 0.

I emphasize this because in most of your under graduate courses, you have not encountered situations in which h can be negative, but as onemovetowards research one must be prepared and alert to the fact thath could also be negative. T ref is an important quantity because it is defined in different flow situations differently, but for the time being,we will say that T ref is known or is knowable somehow.k f is the conductivity of the fluid.So, in order to define h completely, we need to know q w,T w, and T ref.

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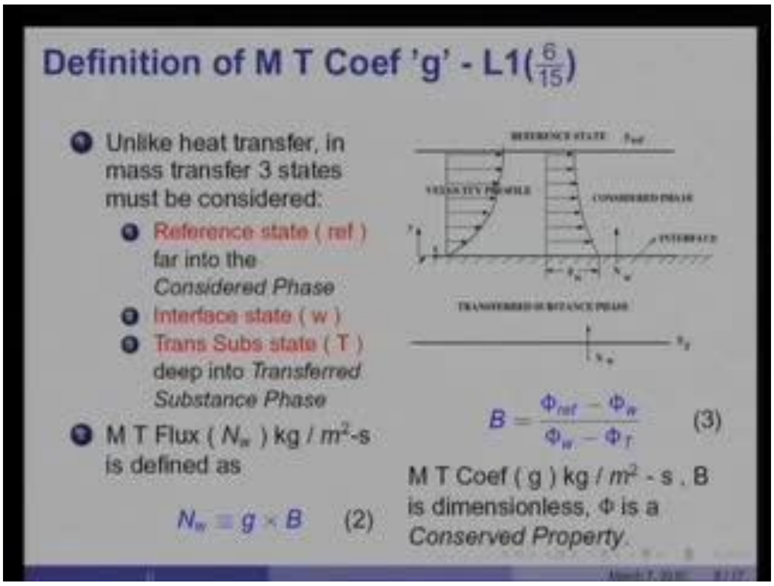

Definition of M T Coef 'g' - L1($\frac{6}{15}$)

- Unlike heat transfer, in mass transfer 3 states must be considered:
  - Reference state (ref) far into the *Considered Phase*
  - Interface state (w)
  - Trans Subs state (T) deep into *Transferred Substance Phase*
- M T Flux (N_w) kg / m^2-s is defined as

$$N_w \equiv g \times B \qquad (2)$$

$$B = \frac{\Phi_{ref} - \Phi_w}{\Phi_w - \Phi_T} \qquad (3)$$

M T Coef (g) kg / m^2 - s . B is dimensionless, Φ is a *Conserved Property*.

When defining heat transfer, we referred only to theinterface state and the reference state.Butin mass transfer, we need to consider 3 states:The reference state which is far away from the interface into which mass transfer is taking place,the interface state w, and a third state deep inside that is called the transferred substance phase.

Imagine,for example, that water in a plate is evaporating into the atmosphere.Then we would need to know - what are the conditions deep inside the water, at the surface of the water, and far away from the water, in the ambient air,in order to be able to calculate the rate of evaporation of water from the pond - the mass transfer flux.Here I use the symbol

N suffix w is again a mass transfer rate m dot per unit area.Therefore, ithas units of kilograms per meters square second.

It will be defined as N w equal to g multiplied by B where B is a ratio, is a dimensionless quantity, comprisingany quantity phi at the reference state minus phi at the interface state divided by the phi at theinterface state minus phi in the transfer substance state.Since B is dimensionless, notice that g and N w have the same units - kilograms per meter square second; whereas, in heat transfer, the heat flux and heat transfer coefficient have different units. Phi - for the time being, note that it is a conserved property.What is it?We will see as we go along.

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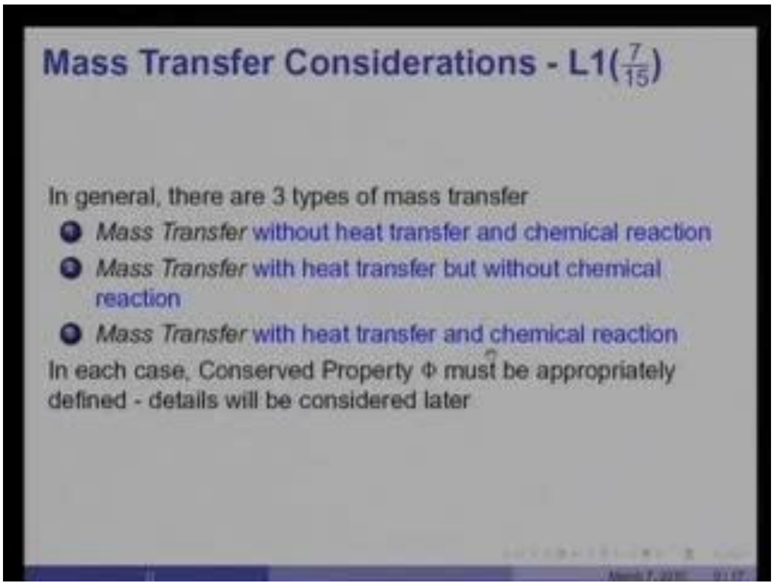

Mass Transfer Considerations - L1($\frac{7}{15}$)

In general, there are 3 types of mass transfer

- *Mass Transfer* without heat transfer and chemical reaction
- *Mass Transfer* with heat transfer but without chemical reaction
- *Mass Transfer* with heat transfer and chemical reaction

In each case, Conserved Property Φ must be appropriately defined - details will be considered later

In general, there are 3 types of mass transfer: The first is mass transfer without heat transfer and chemical reaction, which meansthe water deep inside in the pond, at the surface, and in the considered phase far away from thepond surface - all have same temperature.Therefore, there is no possibility of any heat transfer nonetheless mass transfer would take place; should relative humidity in the ambient air is less than 100 percent then mass transfer would still take place.

Mass transfer with heat transfer butwithout chemical reaction:Now, imagine that the ambient air is hotter than the interface temperature and it is still hotter than thetemperature deep inside the pond.Obviously, there would be heat transfer into the water,but there would be mass transfer accompanied by heat transfer. Of course, evaporation is aninert process.There are no chemical reactions taking place in any of the phases.Therefore,we call it as mass transfer with heat transfer, butwithout chemical reaction.

Finally, the mass transfer with heat transfer and chemical reaction:A very good example of this is the combustion of fuels - solid, liquid or gas, in which for example, when a coal particle burns, mass transfer takes place from the particle into thesurrounding air; heat is transferred from surrounding air to the coal particle continuously,to keep its surface temperature high.There is a chemical reaction at the surface of the coal particle as well as there is a reactionof the released gases in the ambient air.So, in each case, conserved property phi must be appropriately defined and we shall be considering these aspects as we go along.

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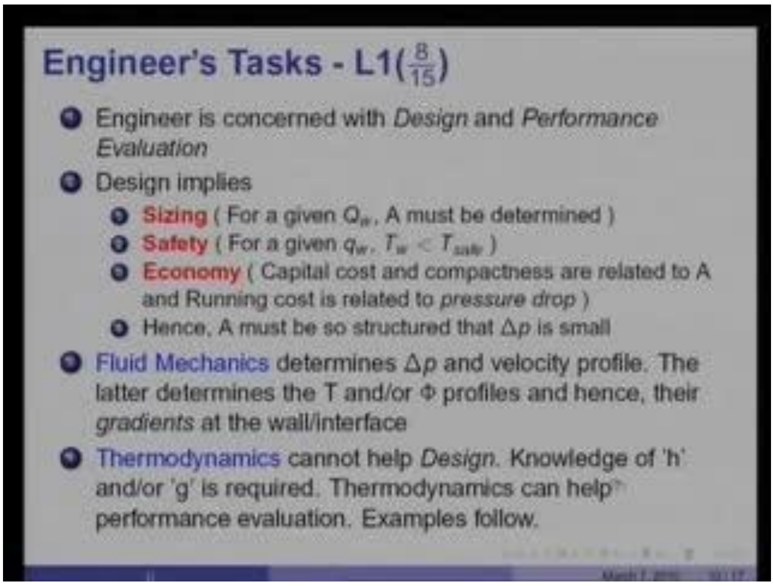

Engineer's Tasks - L1($\frac{8}{15}$)

- Engineer is concerned with *Design* and *Performance Evaluation*
- Design implies
  - **Sizing** (For a given Q_w, A must be determined)
  - **Safety** (For a given q_w, $T_w < T_{safe}$)
  - **Economy** (Capital cost and compactness are related to A and Running cost is related to *pressure drop*)
  - Hence, A must be so structured that Δp is small
- Fluid Mechanics determines Δp and velocity profile. The latter determines the T and/or Φ profiles and hence, their *gradients* at the wall/interface
- Thermodynamics cannot help *Design*. Knowledge of 'h' and/or 'g' is required. Thermodynamics can help performance evaluation. Examples follow.

It is very important torecall the main task of an engineer.The engineer is concerned with design and performance evaluation of practical heat transfer equipments.

Design means sizing.For a given heat transfer rate Q w, how much area should I provide so that the surface never attains a temperature T w and always remains less than some safe metallurgical temperature determined from metallurgical considerations. So, safety is also a very important aspect.Finally, the economy;the capital cost and the compactness of the heat transfer surface is related to surface area A, required to transfer heat Q w, but the running cost is related to pressure drop because the fluids are being moved past a surface. Therefore, area A must be chosen or so structured that the pressure drop is as small as possible and the pumping power is so small reducing therunning cost.

Fluid mechanics determines delta p as well as the velocity profile; the profile in turn determines the gradients of temperature and phi profiles at the wall which enables you to calculateh.Note that thermodynamics cannot help design simply because thermodynamics deals with the change of state and not with the rate of change of state.Therefore, if you want to design any practical equipment, what you need to know is the rate of heat transfer per unit area per unit time.That can only be determined with the knowledge of h or g, as the case may be, whether one is considering heat transfer or one is considering mass transfer. Thermodynamics however can help in performance evaluation.

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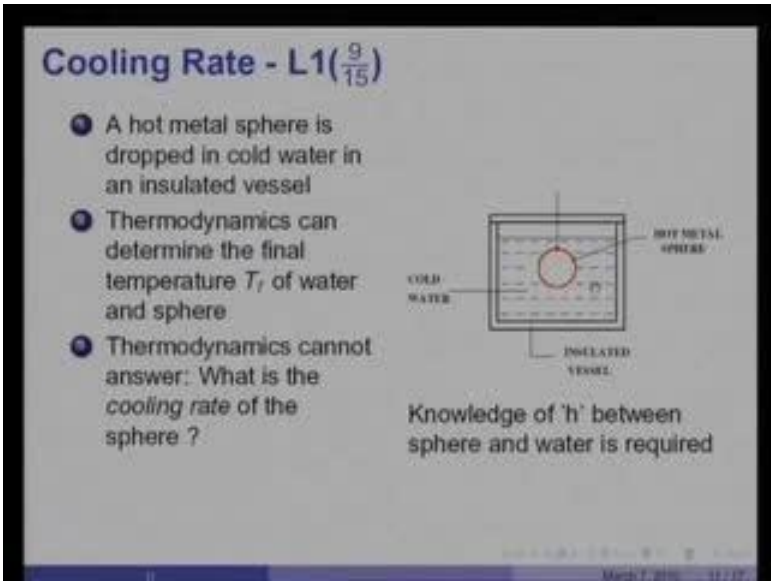

Cooling Rate - L1($\frac{9}{15}$)

- A hot metal sphere is dropped in cold water in an insulated vessel
- Thermodynamics can determine the final temperature T_f of water and sphere
- Thermodynamics cannot answer: What is the *cooling rate* of the sphere ?

Knowledge of 'h' between sphere and water is required

We shall see the importance of thermodynamics andits relation to convective heat transfer in the examples that follow.

Here,I consider the very simple example of a hot metal sphere which is suddenly dropped into cold water and the water is held in a perfectly insulated vessel. Obviously, as the time progresses, the metal sphere will cool down and the water will heat up.Ultimately, both of them will attain the same temperature.Let us call this temperature TfinalT f.Thermodynamics will readily tell you what this final temperature will be because the heat lost by the sphere would equal the heat gained by the water.If you know the mass and specific heat of the sphere and water, you could readily determine the final temperature T f.

Thermodynamics however cannot answer the question - what will be the cooling rate of the sphere?In other words, what will be the rate of change of temperature with time of the sphere?Nor can it readily determine - what will be howor rather how long it will take to reach T f the final temperature?

If you want to determine the time required for the sphere to read the final temperature, you would need to know heat transfer coefficient between the surfaceof this sphere and the water that surrounds.In this case, the heat transfer would be by natural convection because we assume that the water is stagnant and motion in it is induced simply by the density gradient setup by the temperature differences.

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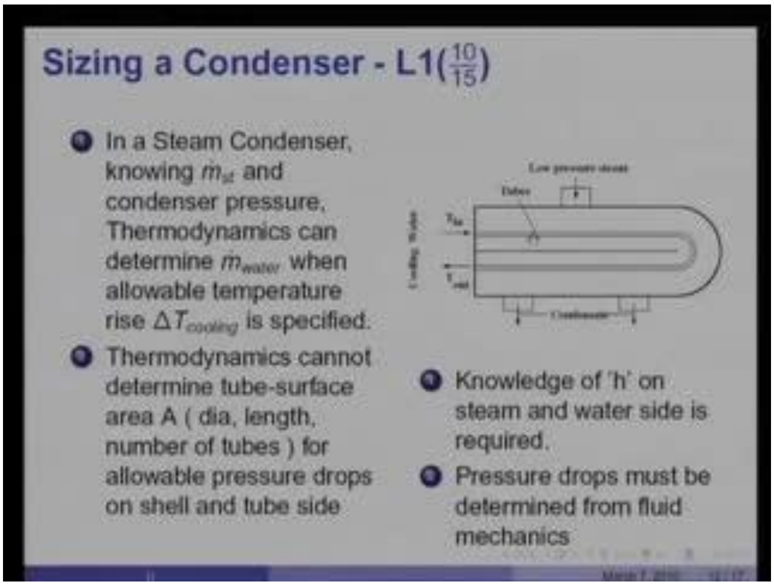

Sizing a Condenser - L1($\frac{10}{15}$)

- In a Steam Condenser, knowing $\dot{m}_{st}$ and condenser pressure, Thermodynamics can determine $\dot{m}_{water}$ when allowable temperature rise $\Delta T_{cooling}$ is specified.
- Thermodynamics cannot determine tube-surface area A (dia, length, number of tubes) for allowable pressure drops on shell and tube side
- Knowledge of 'h' on steam and water side is required.
- Pressure drops must be determined from fluid mechanics

We take another example of sizing a condenser.So, considera condenser in which a low pressure steam is coming in on the shell side,whereas the cold water or the cooling water is passed into the tubes inside the condenser.The cooling water will enter at a low temperature T in and would come out at the temperature T out.The steam would condense and the condensate would be collected at the bottom of the condenser.

So, in a steam condenser, knowing the mass flow rate of steam and the condenser pressure, thermodynamics can determine the mass flow rate of cooling water required when the allowable temperature difference Tout minus T in is specified.The difference T out minus T in is specified simply because often temperature of water coming out of the condenser is let off into a pond or a creek.

In order to save the marine life,for example, one would specify that T out should not exceed32 to 33 degree centigradebecause it isif hotter than that, then it is harmful to marine life. So, thermodynamics will tell you what the mass flow rate of water should be, for a given mass flow rate of steam.However, what thermodynamics cannot tell you is - how many tubes will be required or in other words what would be the surface area required at the interface between the tube and the steam? For example, its diameter, length, number of tubes etcetera.

The actual pressure drops are less than the allowable pressure drops on both shell and the tube side that can only be determined by knowledge of h on the steam side and on the water side in the tubes.Pressure drops must then be determined from fluid mechanics, knowing the fluid flow rates on either side.

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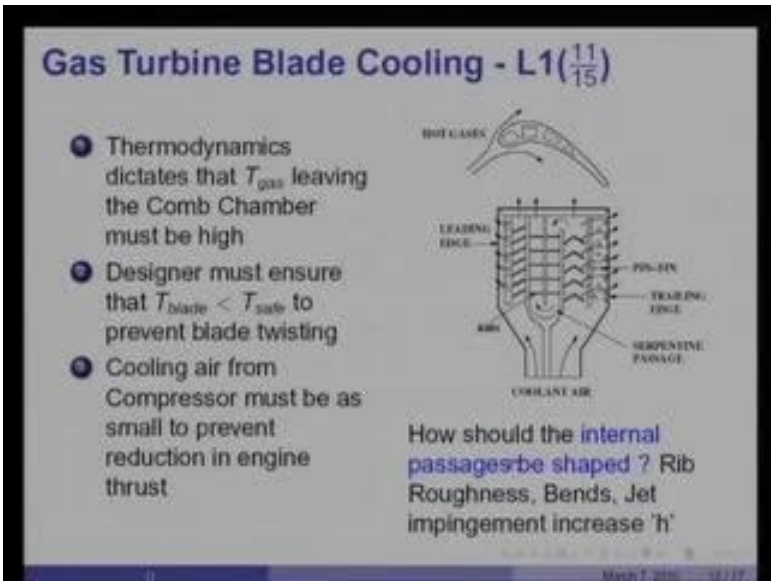

Gas Turbine Blade Cooling - L1($\frac{11}{15}$)

- Thermodynamics dictates that T_{gas} leaving the Comb Chamber must be high
- Designer must ensure that $T_{blade} < T_{safe}$ to prevent blade twisting
- Cooling air from Compressor must be as small to prevent reduction in engine thrust

How should the internal passagesbe shaped ? Rib Roughness, Bends, Jet impingement increase 'h'

Here is another example of gas turbine blade cooling. Of course, thermodynamics tells us that the temperature leavingthe combustion chamber of a gas turbine must be as high as possible so as to achieve high thermal efficiency of the turbine. Today temperatures of the order of 1500 to 1900 k are expected in practical gas turbines.These hot gases, however flow over turbine blades.

The designer must ensure that the blade temperature anywhere in the blade will be always less than a safe temperature defined by metallurgical limit in order to prevent melting. But also because some temperature gradients are inevitable inside the turbine blade, the gradients must not be high so as to cause warping or twisting of the blade.That will destroy its hydrodynamic performance.Therefore, in designer has to provideextremely complicated cooling systems in thisfigure.

So, the cooling air from the compressor is brought in from within the blade and made to pass through serpentine passages or blade passages as shown near the leading edge and also pin thin passages near the trailing edge which is extremely thin and the pin thins provide the strength to the trailing edge.

The amount of air that you draw from the compressor to bring about cooling of the blade must be small because you have pressurized the air.It is no point losing some of that air for the cooling purposes because when it comes out of cooling, the amount of air passing over the blade for generating the power would be reduced.Therefore, the amount of thrust produced by the engine is also reduced. Therefore, a designer has to make several compromises.He must obtain high heat transfer coefficients inside the blade so that its temperature is low and he must make sure that the amount of cooling aid required to do this is also very small.

So, the question then arises - how should internal passages be shaped?What I have shown is a very typical arrangement inside a blade (Refer Slide Time: 21:24);for example, in order to increase heat transfer coefficient rib, roughness is employed.These are the ribs.You will see some are at right angles to the flow, some are angle to the flow; it also employs bends.Fluid is made deliberately to go through bends because bends obtain a good heat transfer and there is also jet impingement.As you can see here, near the leading edge from this passage, there is a perforated wall so that the air actually impinges on the leading edge of the blade and cools the blade (Refer Slide Time: 21: 49).

Likewise, at the trailing edge, there arepin fins as to provide strength to the trailing edge as well as impingement heat transfer.In order to make sure that there is no concentration of stress due to temperature gradients in this regionof the blade, these techniques improve the heat transfer coefficient, roughness, bends, jet impingement, etcetera.

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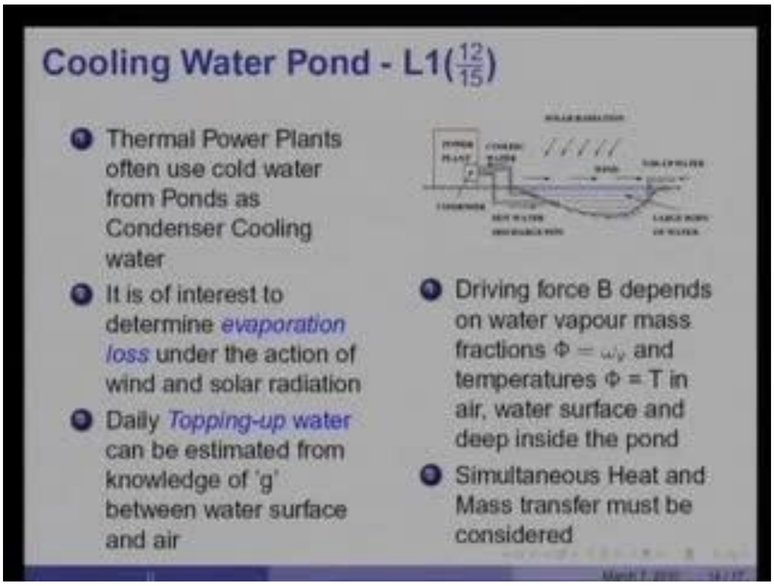

Cooling Water Pond - L1($\frac{12}{15}$)

- Thermal Power Plants often use cold water from Ponds as Condenser Cooling water
- It is of interest to determine *evaporation loss* under the action of wind and solar radiation
- Daily *Topping-up water* can be estimated from knowledge of 'g' between water surface and air
- Driving force B depends on water vapour mass fractions $\Phi = \omega_v$ and temperatures $\Phi = T$ in air, water surface and deep inside the pond
- Simultaneous Heat and Mass transfer must be considered

Let us take another example from a thermal power plant.So, here is a thermal power plant with this condenser.The power plant is taking cool water from the pond and releasing back hot water into the pond again, but the pond is exposed to ambient -solar radiation as well as wind velocity.Therefore, there is evaporation - loss of water and therefore, the pond needs to be topped up with water brought from elsewhere.It is very important to determinethe topping of water requirement for such a pond.To determine such requirement, one would need to know the mass transfer coefficient between the water surface and ambient. The driving force B in this case would depend on water vapor, mass fractions in the ambient at the surface and deep inside the pond, as well astemperatures in the ambient surface and deep inside the pond.

So, we have a situation of simultaneous heat and mass transfer, butwithout chemical reaction because both the air and water do not participate in any chemical reaction in this evaporation process.

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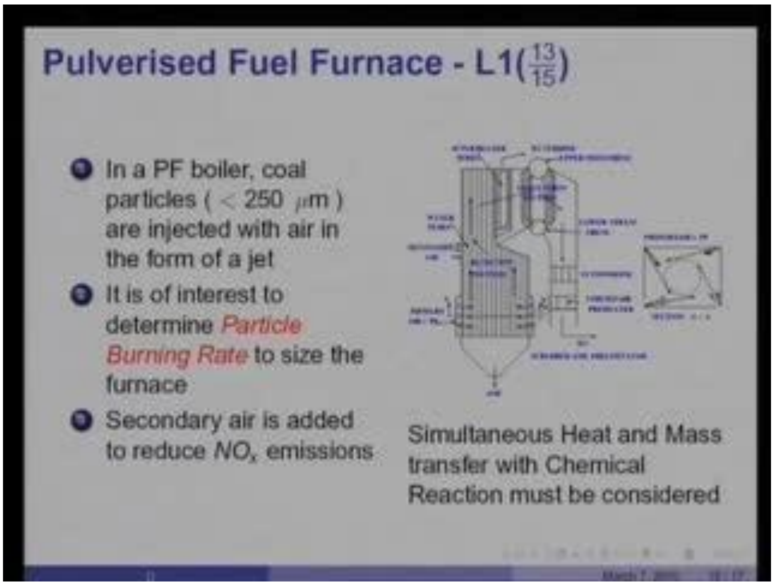

Pulverised Fuel Furnace - L1($\frac{13}{15}$)

- In a PF boiler, coal particles ($< 250\ \mu m$) are injected with air in the form of a jet
- It is of interest to determine *Particle Burning Rate* to size the furnace
- Secondary air is added to reduce NO_x emissions

Simultaneous Heat and Mass transfer with Chemical Reaction must be considered

I now take another examplefrom the thermal power plant that of a pulverized fuel furnace.So, in pulverized fuel furnaces of the type shown or the boilers are shown whole particles typically less than 250 microns are injected along with airin the form of jets from the burners which are located somewhere near the bottom of the furnace.

If I take a cross section aa at this point, it would be something like this and the burners are situated in the corners of the cross section. Thecoal particle and air are injected in this manner (Refer Slide Time: 24:23) so as to provide good mixing inside the furnace.The particles burn inside and release heat. The heat is then transferred to water tubes which are lined along the walls of the furnace and the heat transfer to the water tubes is by convection as well as by radiation because the gas inside the furnace is a transparent medium.The gases then flow over super-heated tubes and then flow through the economizer and air preheater toelectrostatic precipitator.

What is of interest in such a situation is the heat and mass transfer orthe heat transfer by radiation and convection to the water tubes.But more importantly, the particle burn rate.What is the rate at which these particles are going to burn so as to make sure that the height of the furnace is sufficient andall particles are completely burnt before the flue gases go out through their exit?

Nowadays,secondary air is also added somewhere above where the nozzles are or the burners are in order to lower the temperature of the hot gases and thereby reduce NO x emissions.All these environmental considerations would require, nowalong with the power production considerations would require, simultaneous heat and mass transfer with chemical reaction at the coal particle surface as well as in the released gases.

So, we have a situation of simultaneous heat and mass transfer with chemical reaction in a pulverized fuel furnace.In fact, the entire field of convection is called upon in a pulverized fuel furnace because boiling takes place in the water tube that is a heat transfer with phase change.Radiation takes place, convection takes place, mass transfer takes place because there is burning involved and chemical reaction involved. So, we have the most complex situation of convection in a pulverized fuel furnace.

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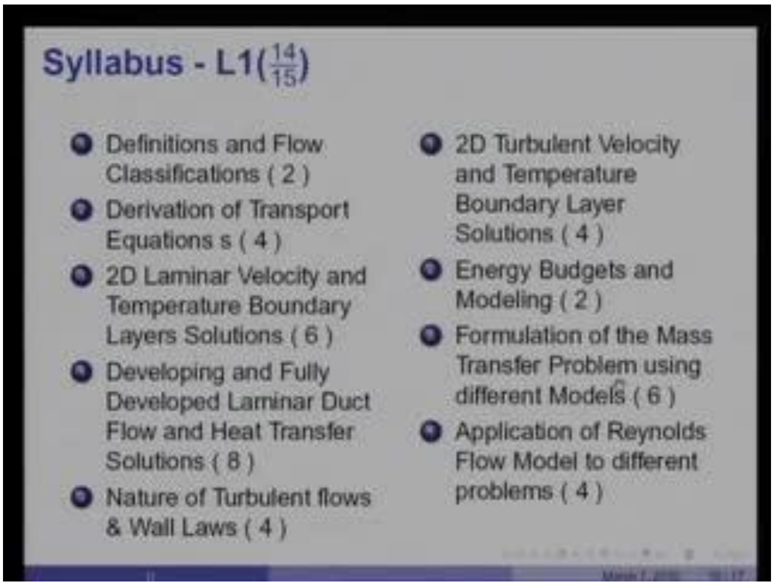


Syllabus - L1($\frac{14}{15}$)

- Definitions and Flow Classifications (2)
- Derivation of Transport Equations s (4)
- 2D Laminar Velocity and Temperature Boundary Layers Solutions (6)
- Developing and Fully Developed Laminar Duct Flow and Heat Transfer Solutions (8)
- Nature of Turbulent flows & Wall Laws (4)
- 2D Turbulent Velocity and Temperature Boundary Layer Solutions (4)
- Energy Budgets and Modeling (2)
- Formulation of the Mass Transfer Problem using different Models (6)
- Application of Reynolds Flow Model to different problems (4)

Let me run through very briefly, the syllabus.The numbers in the brackets indicate roughly the number of lectures I will take on each of these topics.

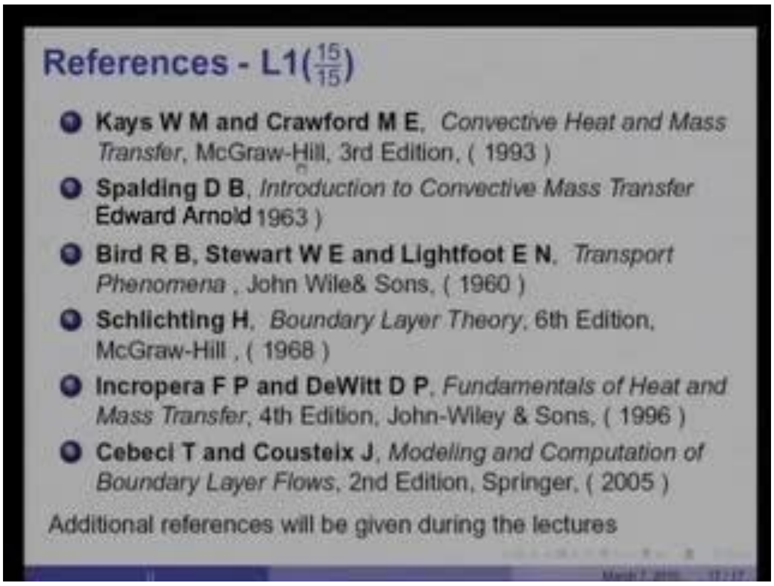
The first topic would be definitions and the flow classifications.The second lecture would consider the flow classification.Then,I shall derive the equations ofmass,momentum energy which are also called the transport equations.I will then consider a very special class of flows called laminar boundary layers and in 2 dimensionsbecause in a classroom one can only consider 2 dimensional problems.

I would then considerducted flows because they are most commonly occur,inhibit changes and firstly I would develop laminar duct flow and heat transfer solutions.I would then turn to turbulent flows because they are most commonly occurring in almost all our heat transfer equipments.Then,I will develop like in laminar case,solutions to 2D velocity and temperature to boundary layers as well as to ducted flows; then I will spend a couple of lectures on what is called turbulence modeling which requiresdrawing up of energy budgets inflows; here, by energy,I mean kinetic energy of turbulence.So, the first set of lectures would be concerned with fluid flow and heat transfer.Then,I would turn to mass transfer.

I would be spending 6 lectures on formulating the total mass transfer problem:mass transferwithout heat transfer and chemical reaction, mass transfer with heat transfer but without chemical reactions, and mass transfer with heat transfer and with chemical reactions.

So,I will develop that problem as a whole and I will be developing sub models which would enable us to determine the value of the mass transfer coefficient from knowing the value of the heat transfer coefficient in the corresponding situations.These sub models essentially depend on postulate of analogy between heat transferand mass transfer. But it is very important to understand the nuances that are involved in this formulation of sub models.Out of these, I will pick one model called the Reynolds flow model and show how well it applies to practical problems involving mass transfer by way of references.

(Refer Slide Time: 29:23)



References - L1($\frac{15}{15}$)

- **Kays W M and Crawford M E**, *Convective Heat and Mass Transfer*, McGraw-Hill, 3rd Edition, (1993)
- **Spalding D B**, *Introduction to Convective Mass Transfer* Edward Arnold 1963)
- **Bird R B, Stewart W E and Lightfoot E N**, *Transport Phenomena* , John Wile& Sons, (1960)
- **Schlichting H**, *Boundary Layer Theory*, 6th Edition, McGraw-Hill , (1968)
- **Incropera F P and DeWitt D P**, *Fundamentals of Heat and Mass Transfer*, 4th Edition, John-Wiley & Sons, (1996)
- **Cebeci T and Cousteix J**, *Modeling and Computation of Boundary Layer Flows*, 2nd Edition, Springer, (2005)

Additional references will be given during the lectures

I have listed here 6 references, but there are many others.

To my liking, the first reference -Kays and Crawford convective Heat and Mass Transfer; thisMcGraw-Hill Asian, third edition is available and published in 1993is probably the closest to what I shall be doingin my lectures.

In this book, the mass transfer aspect is largely based on a veryexhaustive book called Introduction to Convective Mass Transfer by D BSpalding.It was written in1963, but Kays and Crawford have brought inthe modern notations and has made the entire formulationsmuch easier to access and grasp. A very useful book largely used by chemical engineers is called the Transport phenomena by Bird Stewart and Lightfoot.It is an excellent treatyon fundamentals of aFluid Flow Heat and Mass Transfer.It derives equationsin 3 dimensions which are very valuable and also has very small problems, solved problems in the book, which are also very illustrative; perhaps, the most definitive work on boundary layers from the engineering stand point is the work of Schlichtingpublish the sixth edition of which was published in 1968;the title of the book is Boundary Layer Theory.

A much more modern booklargely used for undergraduate and introductory post graduate courses covering all aspects of heat and mass transferat this levelis by Incropera and

Dewitt, as the fourth edition of it isby John-Wiley and Sons is very much available and it was published in 1996.

Finally, for those of you who wish to take this subject forward and understand where its present status lies, the book by Cebeci and Cousteix is published by Springer and it is called Modeling and Computation ofBoundary Layer Flows.Now, this book really contains material which I shall only elude to because I will not be dealing here with numerical methods of solvingconvective heat transfer problem, but largely be concerned with simpler analytical methods for solving.But more complex situations do require modeling, extensive usercomputers.The book by Cebeci and Cousteix gives you a very good update on the latest developments in this field.

In the next lecture,I shall consider the flow classificationsof interest in convective heat transfer;in particular,those that I shall beconsidering in this course.

Thank you.