Mechanical Measurements and Metrology
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Module - 3
Lecture - 35
Measurement of Stagnation and Bulk Mean Temperatures

This will be lecture number 35 on the ongoing series on Mechanical Measurements. In this lecture, we will be completing the module 3. What we will be doing today in this lecture is to look at the measurement of stagnation temperature or total temperature which is useful or involved in a high speed flows in a fluid like air flows at a high velocity the temperature we would like to measure and there are two temperatures one would like to look at. One is called the static temperature and the other is called the total temperature or the stagnation temperature. We will look at the measurement of stagnation temperature by using different types of probes.

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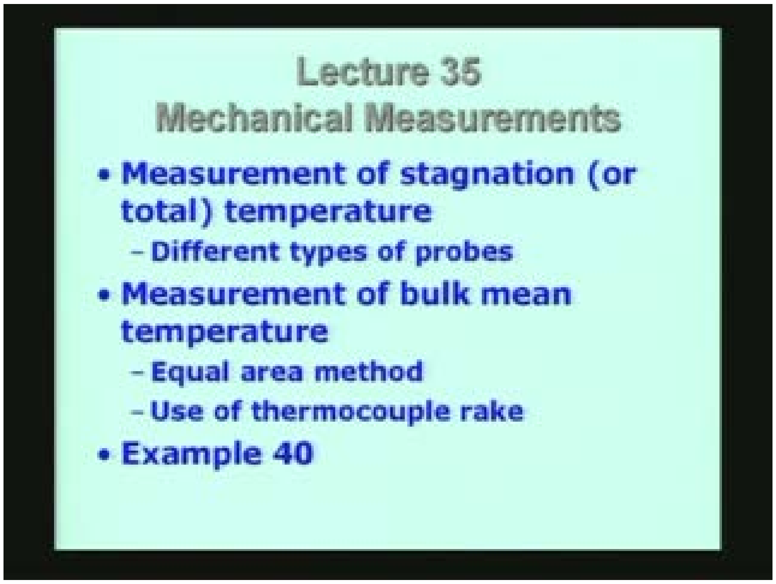

The second thing we are going to look at is the measurement of bulk mean temperature which is required when we want to find out how much enthalpy is transmitted by a moving fluid across. For example, if the flow is inside the duct we would like to find out how much is the enthalpy which is being converted across the section of the duct. So how to measure the bulk mean temperature? There are one or two different aspects of it. Before we go and take a look at the measurement of stagnation temperature, let us just look at the basic ideas which are involved. We are interested in looking at the measurement of the stagnation or total temperature. It is also called the stagnation temperature. And let us look at some of the issues in detail. We can look at the measurement of temperature in terms of the errors in measurement. Let us look at the total error in temperature which is measured and call it E_t this is the total error in the temperature which is measured by a probe. It is made up of several components. The first one is the error due to velocity of the fluid or velocity related E_U, then there could be error due to conduction, which we will call as E_k. So we will say this is conduction error. And thirdly, we have the error due to radiation, E_r. There are three components to the error in the measured temperature. If you want to reduce, for example, if I want to measure the stagnation temperature, the fluid which is flowing at high velocity must be brought to rest or brought to 0 velocity isentropically. If you bring it to rest isentropically, the temperature of the gas or the fluid flowing at high velocity will be actually equal to the stagnation temperature, but as the fluid is brought to rest the convective heat transfer from the medium to the probe which is inserted inside the flow to measure the temperature gets reduced. So, when the velocity is brought to 0, by the stagnation process adjacent to the probe, the heat transfer coefficient is going to reduce. When the heat transfer coefficient reduces, it turns to increase the conduction and radiation errors. Therefore that is the main problem. So we will generally say that velocity tends to 0, convective heat transfer reduces, and both, E_k and E_r tend to increase.

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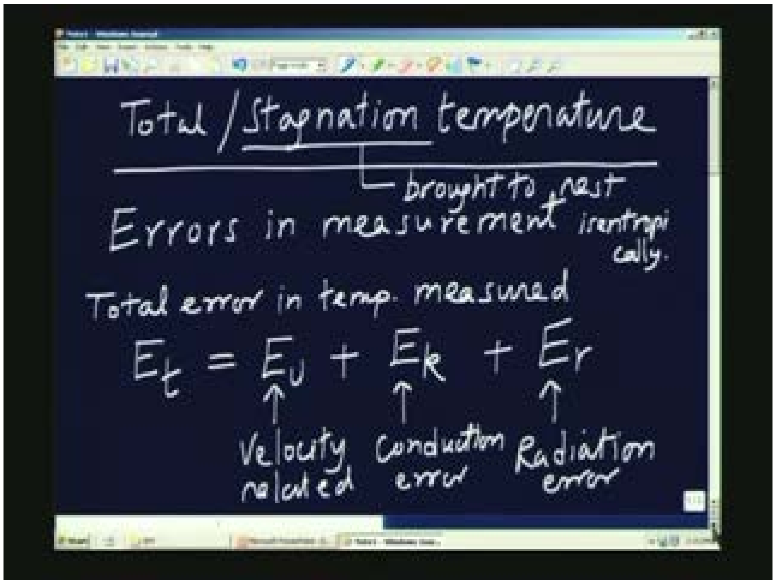

That is the error due to the conduction in the leads of the thermocouple wire which is the part of the probe we are going to use to measure temperature. This is going to become significant. Therefore if you want to reduce the conduction as well as radiation errors, then we have to take suitable actions. To reduce this, of course, radiation can be reduced by using a radiation shield, and the conduction error can be reduced, by making the wires very thin. However, if we make the wires very thin, the gas flowing over the wire or over the probe, is going to induce vibrations in the wire. Therefore it is going to be not satisfactory, and there is some kind of a balance between the strength requirements and the conduction error which we can put up with which will decide the diameter and also the length of the probe wires.

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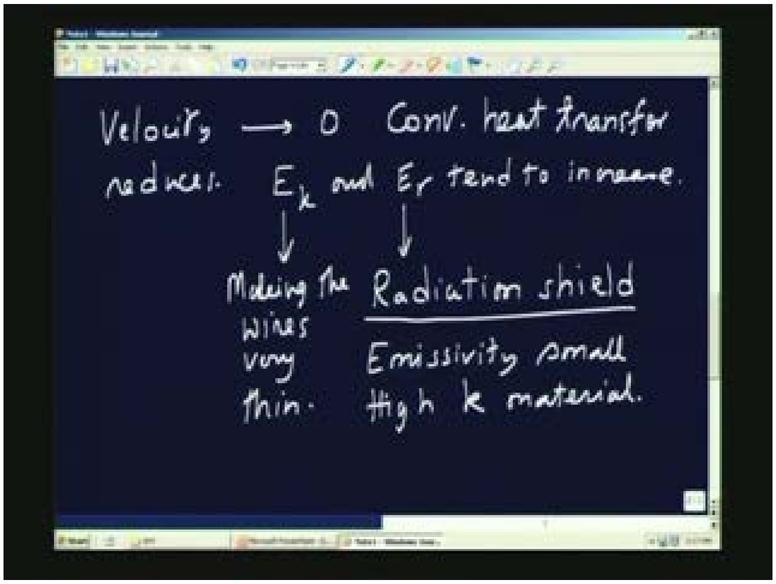

As far as radiation is concerned, we can use shields of low emissivity and possibly high thermal conductivity material. So, the design of the probe for measuring the stagnation temperature requires special consideration.

What are these special considerations?
Suppose, we have a flow at high velocity it may be even supersonic we have to have an arrangement by which the supersonic stream is brought to rest, and we already know that, it is going to give rise to a shockwave across which the pressure will increase and the velocity will decrease from supersonic velocity to subsonic velocity across the shockwave. And after the fluid has passed through the shockwave, it is going to further reduce the speed, and comes to stagnation near the probe.

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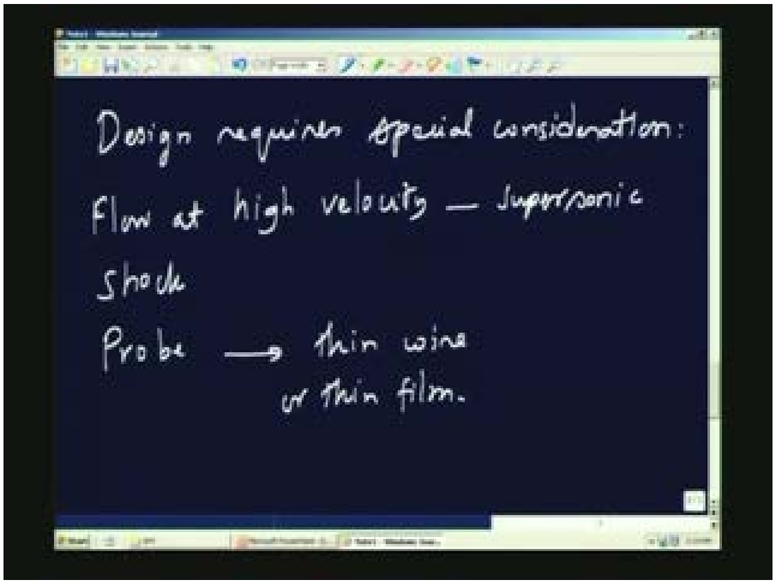

The probe itself may be in the form of a thin wire or it could be a thin film. How to design this is what we are going to look at. So let us look at a typical total temperature or stagnation temperature probe.

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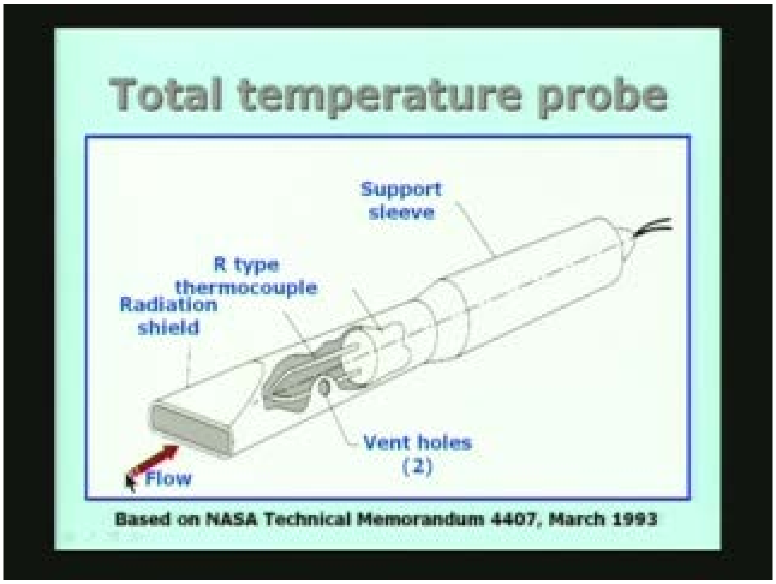

This is a typical example taken from the NASA technical memorandum March 1993. The length from this point to this point here is, about, 50mm may be 2 inches or 15mm. So what we have is, this is a thin radiation shield having an inlet which is very wide and narrow as is indicated here, the flow is coming from this side and it probably has passed through a shockwave, and it is decelerating after going through the shockwave it is going to enter this duct which is in the form of an oval cross section. And it is going to become circular cylindrical cross section downstream which is achieved by having a flattening of the duct. As is indicated, the duct is flattened, and so it becomes an oval cross section here and down stream, I have the R type thermocouple which is having a joint between the two thermocouple wires at this point may be in the form of butt welding the bead is formed right here in this place which is on the axis of the cylinder and the two thermo coal wires are of course taken out through the back here.

And we provide some vent holes on the side. There are two of them one here and one 180 degrees on the other side of the tube. In these vent holes the flow enters the duct type of arrangement here and then it comes to stagnation near the probe and then of course it moves slowly out of the vent holes, because all the medium which comes in must get out and usually the ratios of the areas of the two vent holes provided to the area of the intake is about 0.5 to 0.6 which is found to be the most desirable ratio. That means that the vent holes are smaller than the inlet cross section here.

Now let us look at the basic structure of the flow by looking at (Refer Slide Time: 14:05) the flow from one side. There is a shock here which is in the form of a curved shock which is actually a surface. The flow is coming from here, and the conditions are represented by state 1 and then across the shock it undergoes a change of state to state 2, which is the downstream of the shock and then the subsonic flow actually enters the radiation shield inside. This is the radiation shield part, and the junction is here, and the flow takes place as indicated in this figure, and the flow goes out of the two vent holes on the side.

So it enters from this side and the indicated temperature by the junction is d_j. Actually this temperature which is indicated is not the same as the stagnation temperature, because there is something called the recovery factor. The temperature indicated by the junction is not equal to the total temperature of the stagnation temperature. For finding out the relationship between the junction temperature and the total temperature we use the experimental data which correlates in the following fashion.

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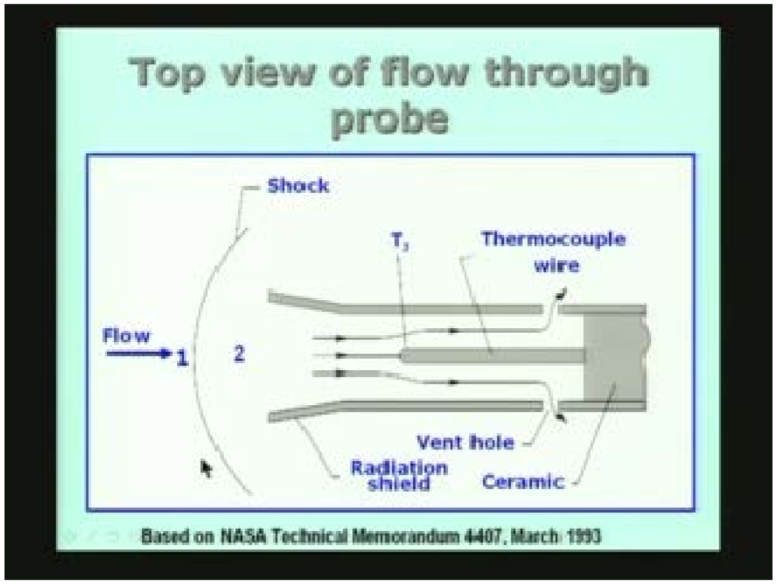

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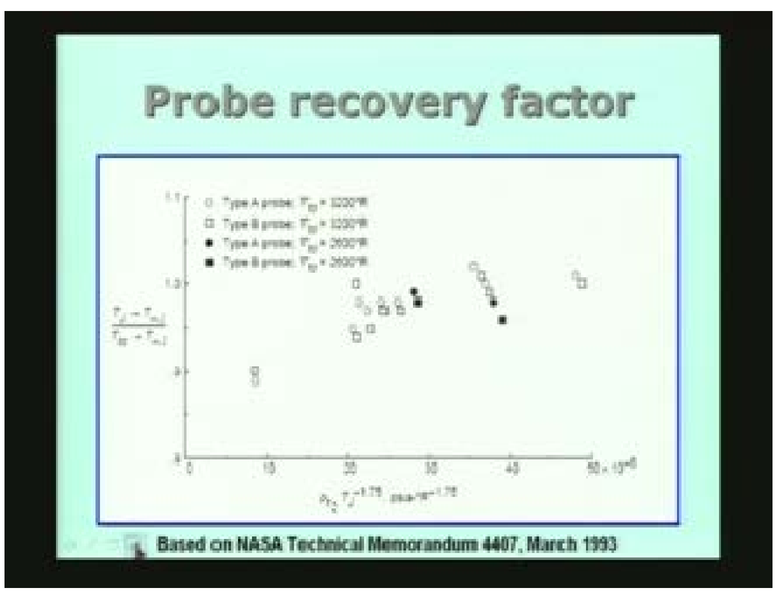

We look at what is called the probe recovery factor. It is defined as the temperature indicated minus the temperature ambient after the shockwave, divided by the total temperature, t_{tc} here, minus the temperature after the shockwave. This ratio is called the recovery temperature and you can see from the graph, which is given here, that the recovery factor given by this ratio of the two temperature differences correlates well with the pressure of the fluid after the shockwave multiplied by junction temperature which is measured to the power minus 1.75. This parameter is called the Winkler parameter, and it is known that, this recovery factor is a function of the parameter pT_2 t_j to the power minus 1.75. Actually we are measuring t_j, we can also measure the pressure by using a static probe pressure probe just after the shockwave so that these two are the measurable quantities. Once we know these two quantities I can find out what is the corresponding value of the recovery factor and once I know the recovery factor, for example, if it is here the recovery factor is about 0.95 then this quantity is equal to 0.95 from this I can find out the total quantity.

So the total temperature is measured indirectly by measuring the temperature indicated by the probe t_j then the temperature after the shockwave, the t_{tc} is the temperature which is required which is now obtained by using the concept of the recovery factor. The recovery factor depends on the nature of fluid, the prandtl number and so on. Essentially it is correlating with this factor the Winkler parameter as shown here.

The stagnation temperature is actually measured indirectly, and the other point to notice is that, this stagnation temperature remains constant across the shockwave because the process is essentially adiabatic there is no heat addition or heat rejection or heat loss therefore stagnation temperature essentially is the same across the shockwave. Therefore whatever the stagnation temperature you measure after the flow has passed through the shockwave and has gone into the probe and whatever indicates it is the same stagnation temperature as the stagnation temperature of the parent gas which is upstream of the shockwave.

This is one type of the probe or measurement of stagnation temperature. Let us look at another interesting way of doing it. This is somewhat different in the sense that, it involves little bit of understanding of what is happening near the stagnation zone. Let us look at the probe. This is taken from paper AIAA 98 - 3131 it is called the dual film stagnation enthalpy probe. Essentially what we have is we have two thin films here, these thin films are actually heat flux gages which happen to be heat flux sensors which are placed very near to the stagnation zone, or stagnation point on a suitably shaped body.

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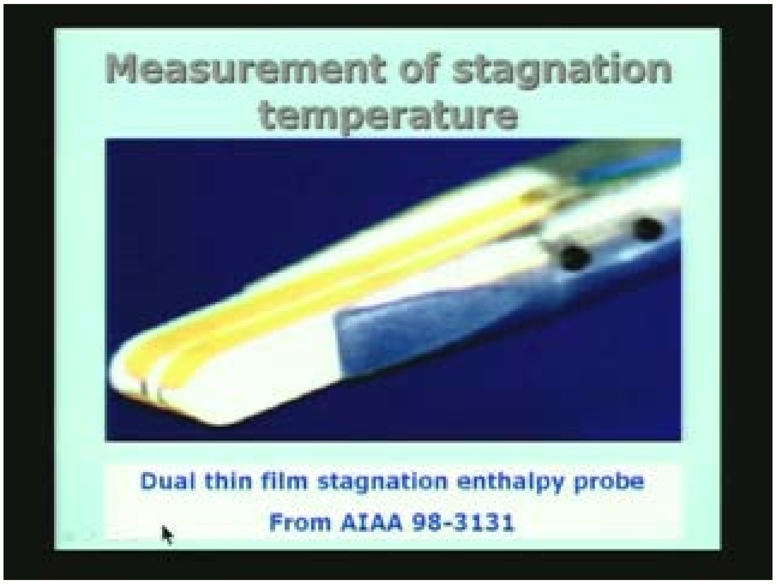

In this case you can see the body is in the form of a bluff body,and at the front stagnation probe two film gages are placed close to each other. Now we heat these two films to different temperatures to start with. By passing a current or by placing a heater just behind the thin film gages we bring the temperature to two different values.

Now suddenly the flow starts at high Mach number and it comes to stagnation near the stagnation point just like what happened in the previous case. At the stagnation point, the heat transfer between the fluid and the film, depends on the temperature difference such as the stagnation temperature or the total temperature and the sensor temperature. So, depending on the temperature of the two sensors which were earlier brought to suitable values the heat transfer will be proportional to the temperature difference between the stagnation temperature and the film temperature.

So what is done is, actually we measure the instantaneous values of the heat flux at the two films. So q_1 and q_2 if we are measuring we also measure the temperature of these two probes at the same time. So T_1 and T_2,q_1 and q_2 are the heat fluxes measured and the temperatures measured then we can do a simple analysis as indicated here which says that the heat transfer rates for the two thin films are given such as for the film which is maintaining the temperature T_1 whose temperature is T_1 at the time of the measurement and q_1 the heat flux which is also measured is equal to some heat transfer coefficient multiplied by the total temperature minus T_1 and q_2 is also equal to the same heat transfer coefficient because the two films are very close to each other or exposed to the same kind of environment and we can assume that the heat transfer coefficient is roughly the same value for the two sensors so $h(T_t$ minus $T_2)$.

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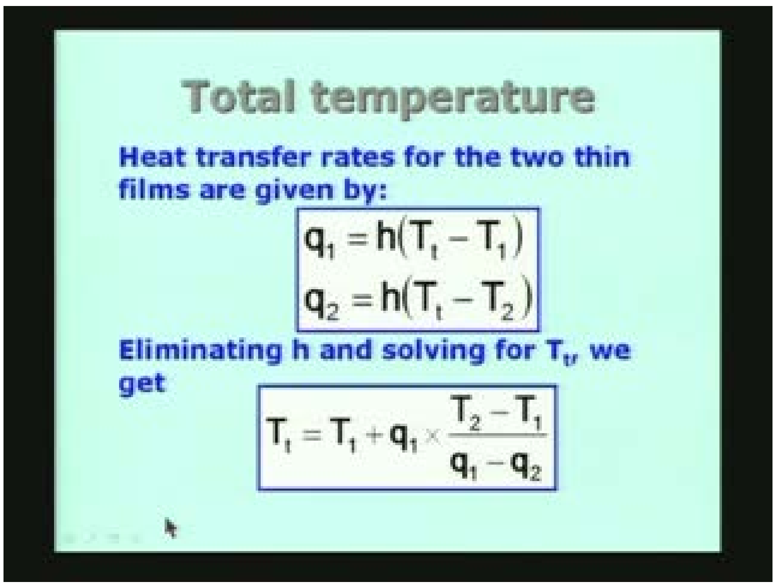

So this T_1,T_2 q_1 and q_2 are measured and for h of course we do not know what the value is so we can eliminate h and solve for T's of 50 here in terms of q_1, q_2, T_1 and T_2. And you can see that the solution gives you stagnation temperature equal to the temperature of the sensor 1, T_1 plus $q_1(T_2$ minus $T_1)$,the temperature difference between the two sensors, divided by q_1 minus q_2. You notice that T_2 minus T_1 is q_1 minus q_2 these are two opposite sides.

Essentially the method consists of using two heat flux sensors of the thin film type placing them close to each other near the stagnation point on a bluff body, measuring the two heat fluxes q_1 and q_2 and the corresponding temperatures of the sensors T_1 and T_2, of course q_1, q_2 should not be the same and T_1 and T_2 must be different and that is why we heat them to different temperatures to start with. Obviously q_1 and q_2 will be different because the potential difference available for heat transfer is the difference between the stagnation temperature and the sensor temperature.

So the sensor temperatures are measured, corresponding heat fluxes are measured using the thin film sensor. Therefore eliminating h I can solve for the stagnation temperature and obtain the value by a simple process. This is a very useful method. Usually in the high speed tunnels where such experiments are done, the process itself goes for a very short period. Therefore these methods are ideally suitable for that and also thin films have very high frequency response and therefore they are suitable for measurement of these values. These are the two different ways of doing it.

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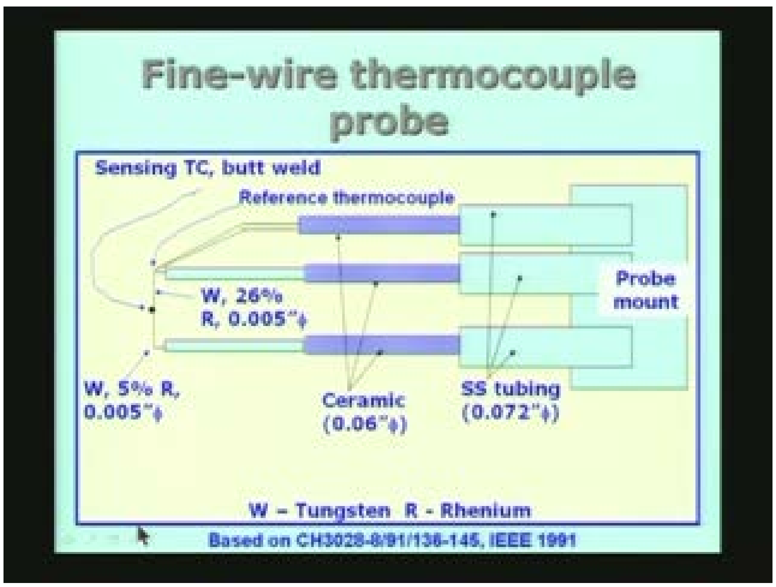

The third method is a Fine-wire thermocouple probe. Essentially we have a very thin wire thermocouple made up of tungsten rhenium 5% against tungsten rhenium 26%. The wires are like here and here, and you see that there is a butt welds here shown as a bead. Actually the bead is very small but it will be the same size as that of the wire itself. This is a butt welded thermocouple. In fact in this stagnation point or stagnation region the flow is coming from this side. Therefore the temperature is indicated by this thermocouple.

So between these two I get the thermocouple reading which is one temperature. Secondly,I am also attaching a reference thermocouple made up of the same thermocouple pair and it is attached at this point. This is called the reference thermocouple. Why do we use this reference thermocouple? I know the cross sectional area of this wire. If I know the temperature which is measured here and the temperature which is indicated in the reference thermocouple, I can in fact find out what is the conductive loss. In other words, the error due to conduction to the probe through the lead wires can be estimated by using simple conduction analysis from here to here. Therefore,I can find out the conduction error by this probe.

The conduction error can be estimated and subtracted or added to the temperature to get the proper value for the thermocouple. Essentially the two wires are taken out as shown here. These two are the same material as the thermocouple material but of larger cross section. Therefore this pair of wire forms the sensing thermocouple and to the end of this, I have attached the reference thermocouple and these two are taken through here, there is a ceramic sleeve and there is SS tubing taken out and the probe is mounted as shown here.

Again in this case also, we have to worry about the recovery factor or the recovery ratio the ratio of the temperature indicated to the temperature at the stagnation point And it is correlated with respect to the Reynolds number of the flow based on the wire diameter and wire conductivity if the wire diameter in the velocity of the fluid is flowing across it.

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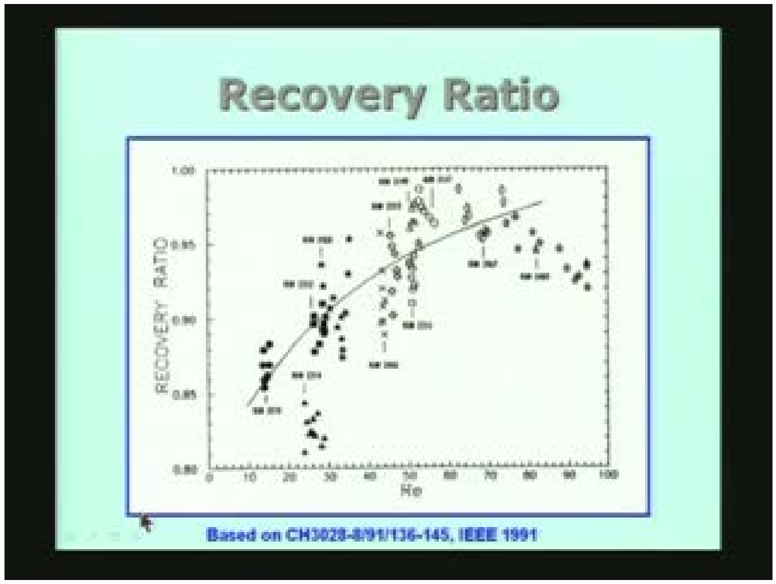

So the data has been gathered from various experiments and basically the full curve here is actually a relationship which is used for calculation. In fact I have plotted that relationship which is given in terms of the temperature measured divided by the stagnation temperature T_0 probe divided by T_0 after the shockwave which is in front and so on similar to the previous case. It is given by relationship with the Reynolds number of the probe. And the Reynolds number can be anywhere between 10 and 100, and the recovery ratio is somewhere between 0.86 and 1 and again recovery ratio is used to identify the proper stagnation.

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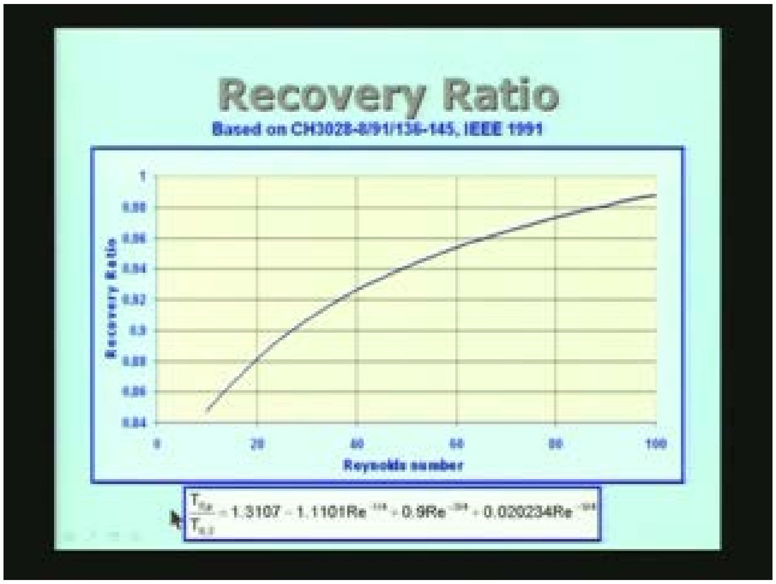

Having looked at the measurement of stagnation temperature, let us look at what is called the bulk mean temperature. Let us look at the concept of the bulk temperature. Actually we would like to look at two things. We will use what is called mean velocity and we will say mean temperature or the bulk mean temperature.

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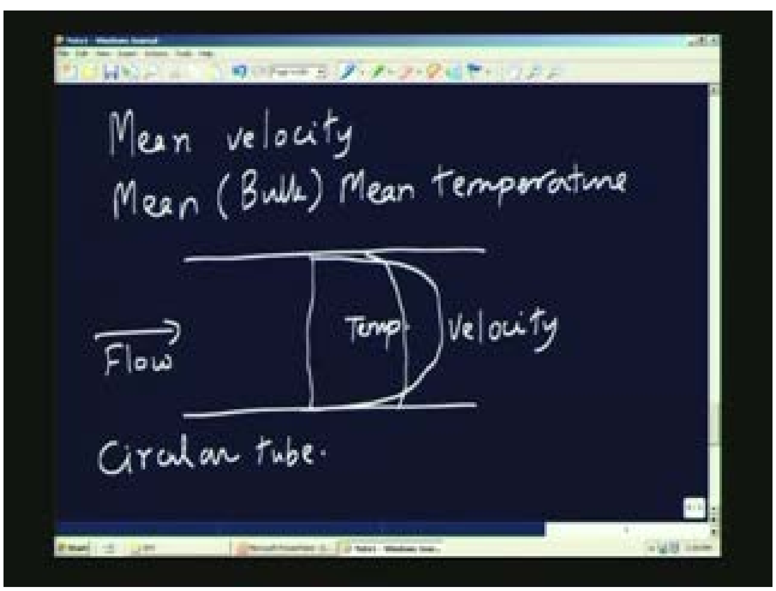

When a flow is taking place in a duct or a tube, if the cross section may be circular or any other shape, the flow is taking place like here, and there is a certain velocity profile and there is a temperature variation across that, this is the temperature. So there is a temperature variation, there is a velocity variation and let me take a simple example of tube flow, flow in a circular tube to explain the concept, but then we can generalize it for any shape of the tube or the duct. If I take a circular tube I can do the following. I can take the cross section this is the R and if I consider a small elemental area, this is the elemental area I am considering so this will be r and this will be dr. So let us assume that, the velocity is a function only of r and may be the function temperature is also a function only of r. That means it is not a function of theta it is uniform and it is given at any radius and it is a radial function of radius only.

We can now see that if the density is rho, specific heat is C_p, these are the density and specific heat and for the present we will assume that it is constant. In fact it can be generalized even when these are not constant. We can see that the enthalpy flux through the elemental area is obviously given by rhoC_pT_u and instead of dA, I can write $2\pi rdr$. Actually this is your dA the area. So I can find out the enthalpy flux through the elemental area as a expression given by rhoC_pT_udA and if I want to calculate the total enthalpy crossing the flux through the cross section if I just total here all I have to do is to integrate from 0 to R. The integration is from 0 to R rho$C_pT_u2\pi rdr$.

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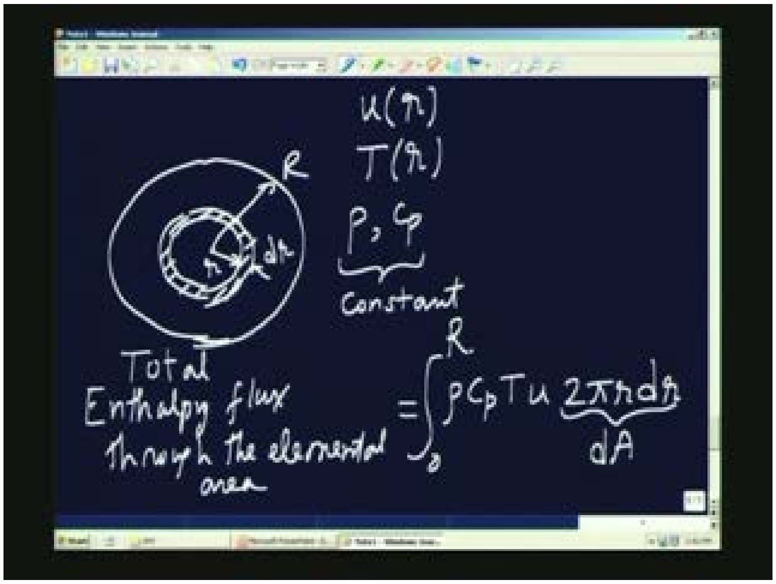

And if I assume that rhoC_p is constant, this can be taken out of the integral sign, this 2π is also a constant and I cannot simply take it out. Therefore you can see that I can rewrite it as, if I assume that rhoC_p are constant then this enthalpy flux, the rhoC_p I will take out, 2π also I will take out, integral 0 to R, (uTrdr) or I can also write as (rhoC_p2π) integral 0 to R,(uTdA) where dA is the area of that elemental ring. Therefore to determine the flux of enthalpy crossing the section I require performing an integration using the values of the velocity.

For example, in that ring element, I can take the velocity at the center of that ring and the temperature also at the center of the ring. That means, I have measured the velocity and the temperature at the center of that ring using a probe, may be a pitot tube can be used for measuring the velocity and temperature can be measured by using a small thermocouple probe inserted in the particular place. In practice, let us see what happens. This is as far as the theoretical framework is concerned. I would also look at what is called the bulk mean temperature which is defined as rhoC_p the bulk mean temperature is defined such that rho C_p into (2π into u bar into T_b) into area of cross section of the tube gives you the enthalpy flux 0. So I have introduced an average velocity, I introduced the bulk. So, if you want to get the bulk temperature, here you can see this will be equal to this and therefore (2πrhoC_p) can all be canceled so you can see that u bar T_b bar A equal to integral 0 to R, (uTdA) and what is u bar? The u bar is nothing but the mean velocity to this and therefore

2π rhoC_p can all be canceled so you can see that u bar T_b bar A equal to integral 0 to R uTdA.

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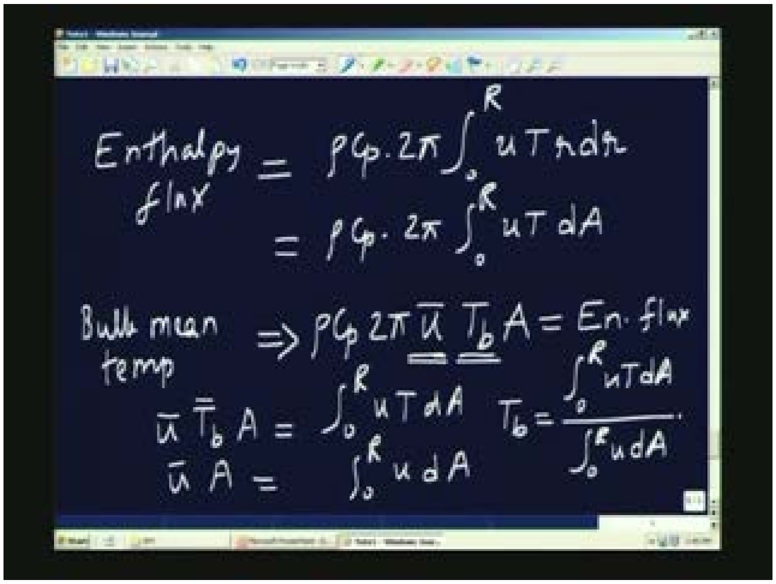

What is u bar?

The u bar is nothing but the mean velocity. The (u barA) by the very definition is nothing but udA and therefore I am going to get T_b which is nothing but integral 0 to R, uTdA. This is the final expression we have got. So what does it mean? It means that to determine how much enthalpy is crossing a section of the tube,I must know the details about how the velocity and temperature vary across the section of the tube. I must be able to perform this integration and then obtain the value of the bulk temperature. Of course,it is very difficult to do this integration exactly. So what we do is, we will use what is called equal area method.

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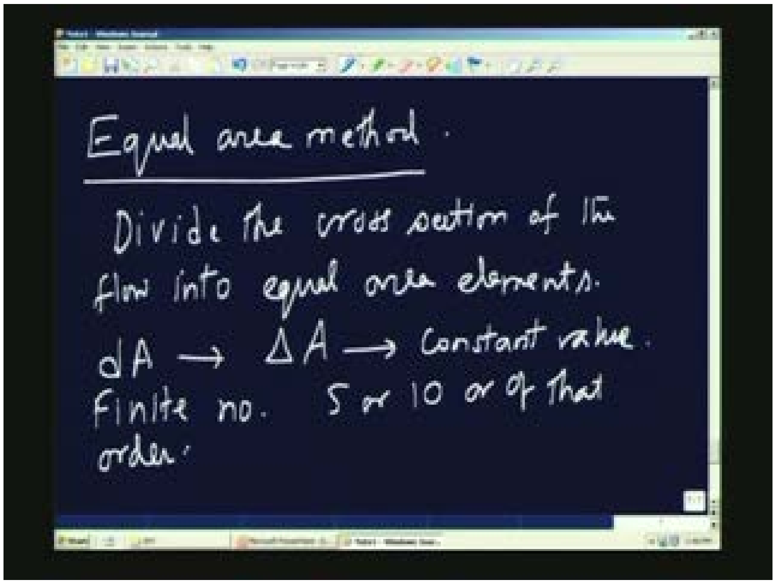

Here we divide the cross section of the flow into equal area elements. Of course, we cannot take too many elements. We will take a certain small number of elements, may be 5 or 10 at the most such that this dA is replaced by delta A which is a constant value. So what we are going to do is divide the flow cross section area into several equal area elements and each area element is now delta A and we have a finite number of them may be 5 or 10,or may be of that order may be a little more. So what we will be doing is we will be replacing the integral by summation.

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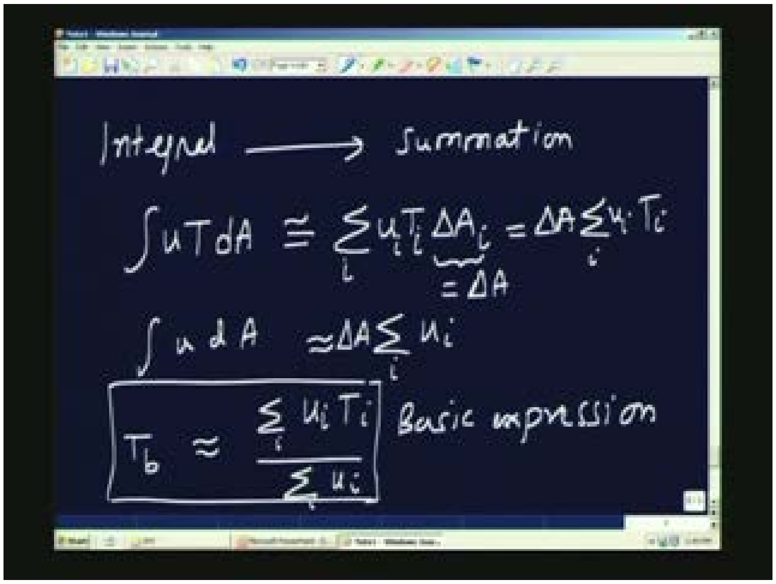

So integral replaced by summation so what I will be doing is this integral uTdA is approximately equal to sigma uT delta A and if I assume delta A are same for all the elements,so I will say i u_i T_i A_i delta i A_i but if delta A_i is constant equal to delta A then this becomes simply delta A multiplied by sigma i $u_i A_i$. This is a very simple expression. Similarly, integral udA will be approximated by sigma u_i (delta A). So you see that bulk temperature now becomes roughly sigma i $u_i T_i$ by sigma u_i. This essentially explains, how the measurement is taken. So this is the basic expression which uses an approximation by replacing the integral or integration by a summation.

The first example is taken from the reference which is given here based on paper presented in congress of observation just to indicate that this kind of method is used in actual practice. We have an internal for testing a heat exchange. Here we have a wind tunnel which provides a more or less uniform flow of air across the cross section of the big duct and the air is taken from the outside through this entrance which is in the form of what is called a bell mouth and the flow is taking place from this side. The flow strengtheners are going to make sure that the flow is a parallel flow inside the duct and duct is usually what is called a short duct. That means the boundary layers which are developed near the boundary is very thin, so that we can assume or we can guarantee that the flow velocity is more or less uniform across the cross section.

And you actually keep the heat exchanger which has to be tested right in the path of the uniform gear stream. And of course you can measure the coolant inlet temperature, outlet temperature for the heat exchanger and for the air inlet temperature we use what is called the rake. The set of thermocouples spaced at uniform facing as shown here. The duct can be in the form of rectangle or square and all you do is to measure one velocity because I indicated the velocity is going to be uniform across the cross section therefore u bar equal to u in this case, and the temperatures are measured by a rake of thermocouples, a rake is what is shown.

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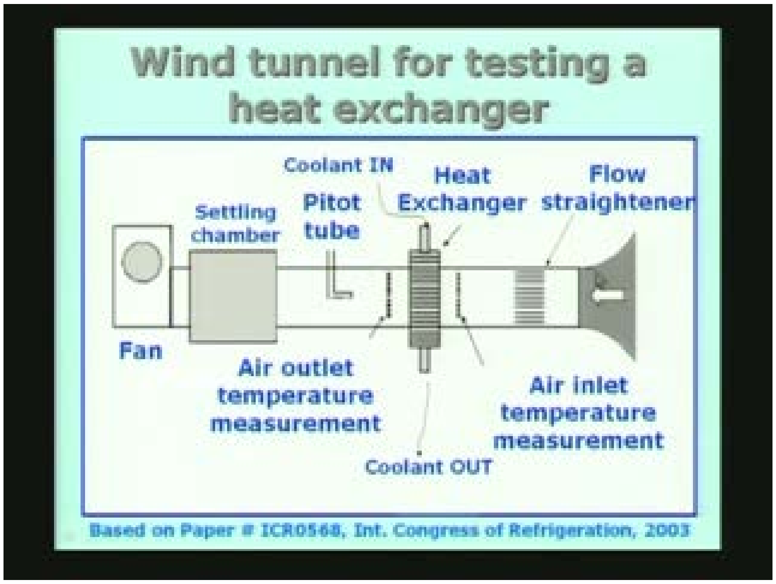

Here, mini thermocouples spaced in a regular array here and another set of thermocouples maintained here and what we do is we measure the bulk temperature at inlet by replacing the integral by summation as indicated. In this case, because the velocity is uniform the arithmetic mean of the temperatures indicated by the thermocouples is also equal to the bulk temperature. Similarly at the outlet because the velocity is more or less uniform, the arithmetic mean of the temperature indicated by the temperature sensors is the bulk temperature of the fluid. So in this example, we are interested in measuring the bulk temperature of the entry and exit to find out how much heat transfer has taken place from the heat exchanger to the fluid which is flowing across.

Actually we are trying to measure the heat transfer and in order to measure the heat transfer we have to measure the bulk temperature increase as far as the air is constant in this particular case. The second example I am going to take uses the equal area method, and I have a duct which is in the form of a rectangle and I have divided into equal area elements as indicated here. These dash lines indicate the boundaries of the equal area element and the dots or the circles indicate the location where the velocity as well as the temperature is measured. It is a simultaneous measurement of velocity and temperature.

Of course it is not possible, but we can measure the temperature at one step and the second step you can measure the velocity. You can use a velocity probe like a pitot tube and you can use a temperature probe in the form of thermocouple. In fact, what we do is we use an array of thermocouple 1 2 3 4 5 so 4 thermocouples in this form of what is called a rake and the rake is moved in this direction by stepping it from this position to this position from here to here and so on by having some arrangement which it can be moved from position to position we can measure simultaneously the temperature at this position and this column and this column and so on. The theoretical basis is that the temperature velocity measured here is assumed to represent the velocity and the temperature on the average in this particular rectangle which is taken as the unit cell. This is delta A. In this case you can see there are 6 into 5 equal to 30 area elements. So you measure 30 temperatures and 30 velocities and you get the mean temperature by taking the summation sigma $u_i d_i$ from i equal to 1 to 30 by sigma u_i where i equal to 1 to 30 again.

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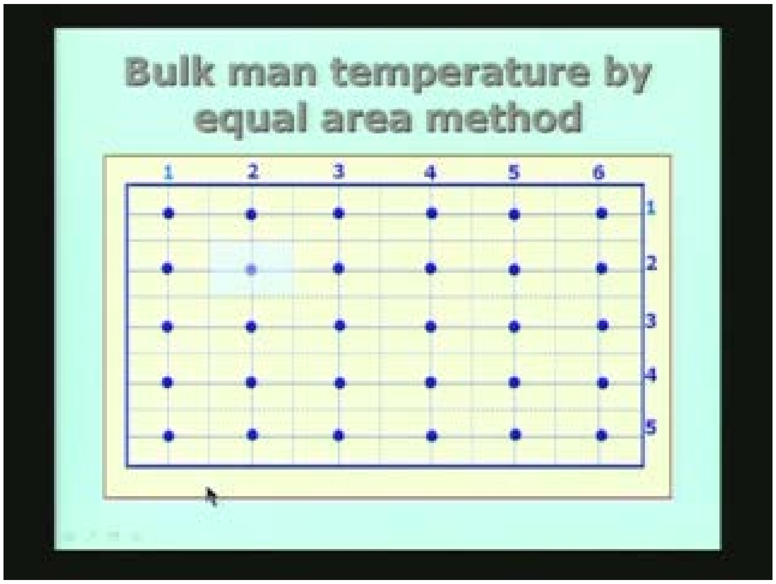

So let us look at the way it is accomplished in practice. We have a rectangular duct here. We have a thermocouple rake here which consists of 4 or 5 thermocouples which are capable of moving by using the traverse it can move in this direction or in this direction. Of course in this case what we do is we position the traverse such that it is in a fixed position in the y direction and we move it along the x axis to get a certain number of columns over which the measurement is taken. By using the traverse it can move in this direction or in this direction. Of course in this case what we do is we position the traverse such that it is in a fixed position in the y direction and we move it along the x axis to get a certain number of columns over which the measurement is taken. So by moving in this particular direction in and out the rake will measure the temperatures at the nodal values.

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This gives you an idea as to 1 2 3 4 5 so 1 2 3 4 is about 20 so an array of 20 values, the anemometer is shown here which is again moved from position to position to measure the velocity variation so this anemometer is moved in and out.

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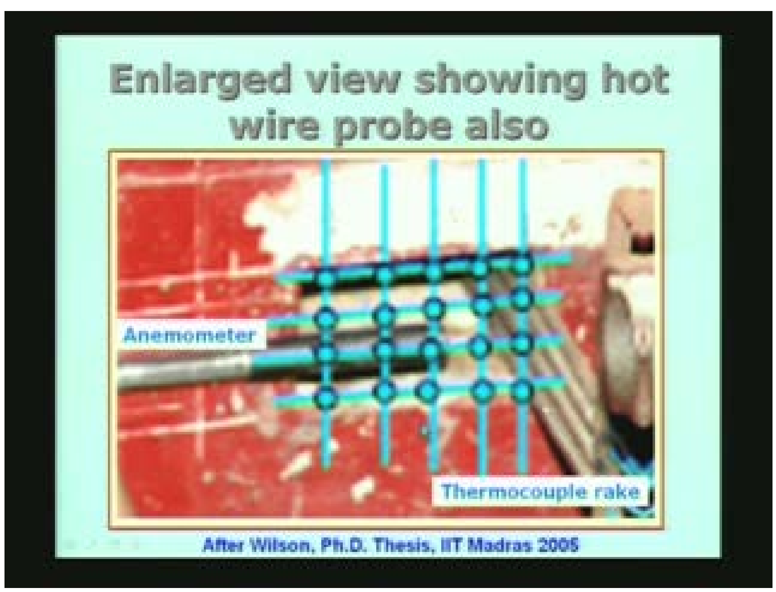

Of course, we have only one anemometer here therefore we move it from one position to another position individually and take the values of velocity, the thermocouple rake measures simultaneously four temperatures and there are five columns so it is 20 values of the temperature are going to be obtained from this experiment.

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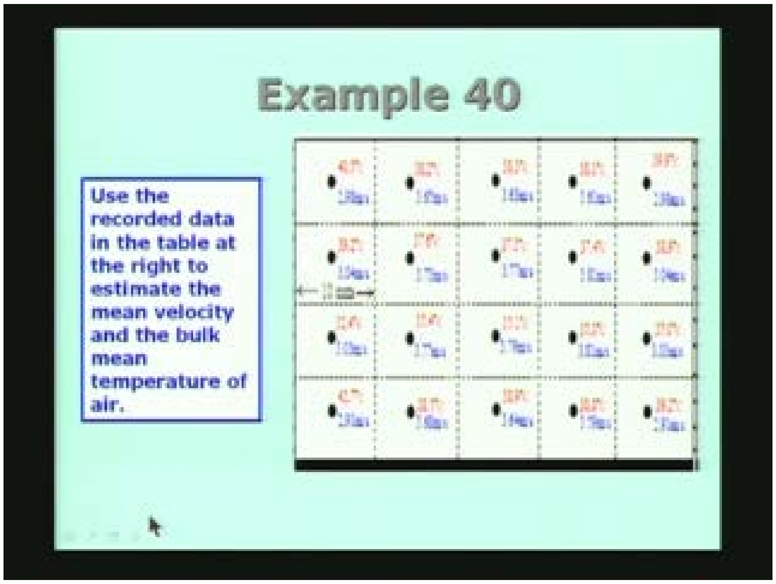

From the recorded data the idea is obtain the values of the bulk temperature as well as the mean velocity. So the example 40 I have taken is actually from the experiment conducted in the laboratory and what we want to do is use the recorded data in the table at the right to estimate the mean velocity and the bulk mean temperature of the medium which is air in this particular case. Of course the velocity which was used is very small, the maximum value is about 3. 65m, 3.77m, 3. 8m and the minimum measured is about 2.98.

The red values are the temperatures which are indicated by the thermocouple by the rake which is moved from position to position, the blue values are the values of the velocity measured is in the velocity probe which is actually a hot film probe which is moved from position to position to indicate the velocity. So what I have done is I have put the whole thing in the form of a table, and the cell numbers are given like 1.1, 1, 1 1, 2 etc like in the formula matrix we can go here and see 1, 1 will correspond to this like 1, 1, 2 1, 3 and so on.

So they represent different cells and the values at the center of each cell are put in the form of the table. In this case, I have used excel to enter the numbers; u m by s 1, 1 to 2. 2, 5 and then 3, 1 to 4, 5 as you can see there are 20 entries, 20 velocities are measured and 20 corresponding temperatures are measured as shown here.

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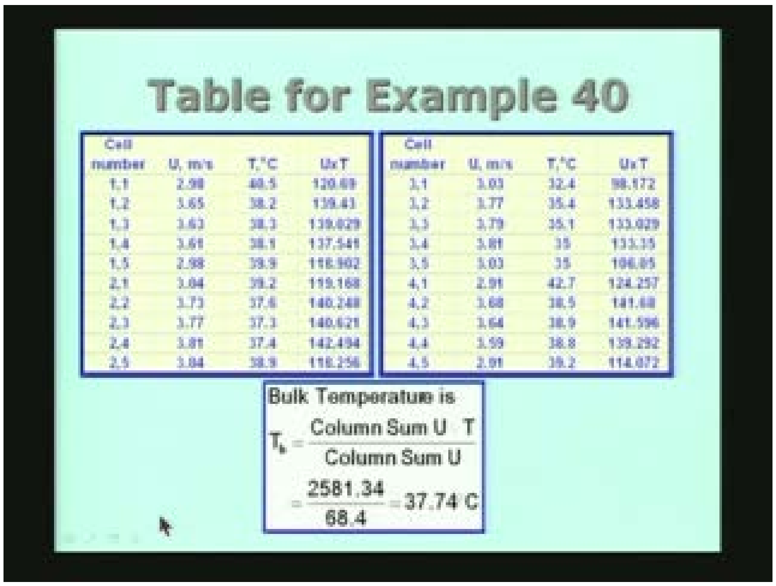

I must also tell you that the velocity being very small, u m by s is only about 3m by s the speed up sound in air is roughly 350m by s so the Mach number is extremely low. Therefore the temperature which is measured is actually the stagnation temperature, because the velocity is very small compared to the velocity of zone the stagnation temperature and the static temperature the difference is very small in the measurement error which is expected in the measurement which you are making. Therefore we are not taking into account the effect of the velocity in the stagnation temperature. That velocity is so small, the stagnation and the static temperatures are very close to each other so we need not worry about that.

But of course, if you want to do similar studies of high velocities, one may have to taken into account the Mach number effect and therefore we have to worry about the difference between the stagnation and the total temperature and the static temperature and so on. Here we have not taken the difference between the two into account. So it is easy to look at the calculation. The area element if you look at this duct is 40 mm by 50 mm and 40 mm tall and 50 mm wide, so I have taken 10 mm by 10 mm as the unit cell. Therefore, as you see here, I have indicated 10 mm this is also 10 mm.

So each one is delta a or the area element is 10 mm by 10 mm because the area element is the same for all the area element shown here the area element size does not come into the picture as far as the calculation is concerned. So, to calculate all you have to do is to measure the velocity and the temperature and the corresponding cell centers and then find out what is the product of U and T and if you want to calculate the bulk temperature all you have to do is to sum for (U into T) this column you have to sum and sum all the values in the last column divided by the column sum for the velocities the second column.

So the column sum themselves can be used for the calculation of the bulk temperature and you see that the column sums are given by 2581.34 the appropriate unit, it is actually degree Celsius (m by s) and the denominator is 68. 4 that is nothing but the sum of all elements in this column. And if you remember earlier we talked about the use of excel you can get the column sums simply by using summation which was indicated there. So what I have done is I have taken the column sum in the numerator and the denominator and by making this ratio I get the bulk temperature as 37.74 degree Celsius. In fact if you average the velocity given in these two the average velocity comes to 3. 42m by s.

Therefore in this particular example,the flow is in a duct of rectangular cross section. The rectangular cross section has been divided into unit cells of 10 mm by 10 mm and the velocities and temperatures have been measured at the center of each one of these unit cells and based on these values and based on the summation replacing the integral I have been able to measure the bulk temperature as well as the mean velocity for the probe. This kind of a measurement is somewhat time consuming,because you have to measure the so many temperatures so many velocities and so on. But it is necessary to do that when the velocity and temperature vary considerably over the cross section of the duct in this case the rectangular duct. In this case of a circular duct you need not measure right across the cross section and only across the radius if you measure it is enough if there is symmetry with respect to angle theta.

If the symmetry is not present it will be necessary to divide the circle also into elements in the same fashion we did here may be in the form of sectors and we have to measure the velocities and temperatures at the center of each one of these small sectoral elements and then use the same procedure for measuring the bulk velocity as well as the mean velocity.With this we actually come to the conclusion of module 3 which tried to look at the measurement of heat flux and then we also looked at the measurement of mean flow velocity by using various techniques and then finally we looked at measurement of mean temperature or the bulk mean temperature and also the stagnation temperature in this case of high speed flow. Thank you.