Introduction to Flight
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Measurements in Compressible Flows
Lecture No. 04.7

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Ok, moving on let us look at how the same system is used in compressible flow, we have so far studied only the incompressible flow, that is what we have studied.

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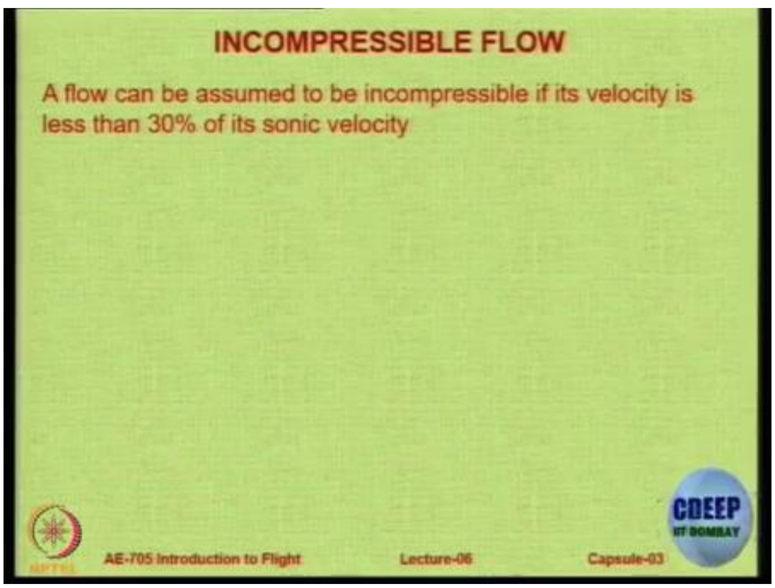

We know from our previous lectures that there is no hard and fast number at which the flow becomes compressible but typically we say that at Mach number 0.3 or lower, you can assume that the flow is incompressible without much error. The errors would be only around 4 to 5 percent at Mach 0.3.

Beyond Mach number 0.3, the errors become increasing, and when you go to Mach number 0.7, 0.8, etcetera, errors becomes very high. So, when you look at incompressible flow then you can apply this version of Bernoulli's principle and if you assume that the altitude is not changing, you are in level flight then the two heights are same. So, you can simply say that at a stagnation pressure the velocity is zero. So, the differences of stagnation pressure divide by rho into 2 is the velocity.

So, this is the principle used by the pitot-static tube in incompressible flow which we have studied so far. Now, we move on to the compressible flow and that too in subsonic and supersonic. So, in compressible flow the fluid is brought to rest, so therefore the kinetic energy of the flow is completely absorbed to increase the stagnation pressure. So, if you have a pitot-static tube like this there is going to be a stagnation pressure in the front.

So, this conversion of energy takes place at the stagnation point, so you get stagnation pressure there. So, the fluid regime can be incompressible, subsonic, compressible or supersonic, it does not matter. The working principle is the same. But the difference is that, now you are using, you are assuming, you are assuming that it is isentropic. Remember now, last time when I spoke to you I asked you to put on moodle a proof that when you bring fluid to rest it is actually isentropic.

No one has so far reported that, no one has been able to put that answer, so still it is open. I would like you to prove that, in a standard pitot-static tube when the flow is regulated and compressed from free stream state that process is isentropic. We have to prove it. So, what we do is the same thing P stagnation and P static are used to measure. So, it is the same principle but the only difference is in how do we get the co-relation between the stagnation and static pressure.

In the, in case of compressible flow the relationship is not simply root of 2 into delta P upon density. You have this isentropic compression formula which is applicable.

$$\frac{P_{Stagnation}}{P_{Static}} = \left(1 + \frac{\gamma - 1}{2} M_{\infty}^{2}\right)^{\frac{\gamma}{\gamma - 1}}$$

So the ratio of P stagnation by P static is 1 plus Ma minus 1 M infinity square gamma upon gamma minus 1. This we all know, using this you can get the velocity formula, a bit different from what was there in previous part. So, this kind of a compensation is, has to be brought in the system when we are looking at a compressible flow.

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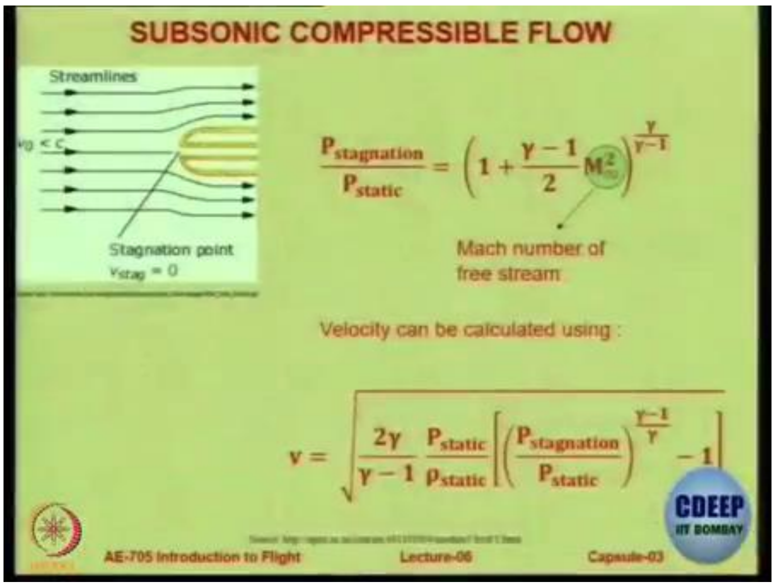

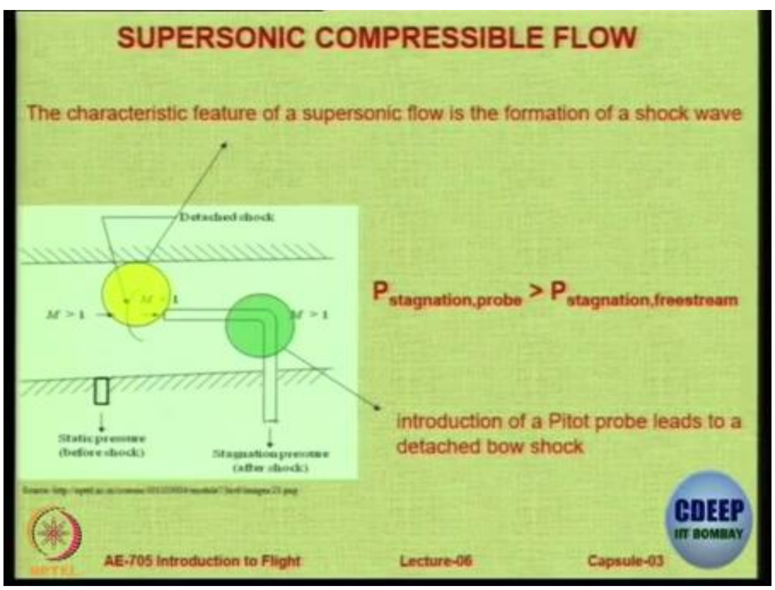

Right. Now let us look at supersonic flow. In supersonic flow, what will happen is that the presence of this tube is going to create a shock. Now, in the next capsule we are going to look at shock waves. We are going to look at this in more detail. So I had a choice, either to discuss this portion at that point of time; but I thought let me just complete it here so that it is there at one place and we do not have to revisit that place once again.

So, right now you have to assume what I am saying. In the next session or in the next capsule I am going to elaborate this into more detail. So, essentially what happens in a supersonic flow is that there is going to be formation of something called as a shock wave. And this shock wave, if it is a blunt shaped body like this or a fairly rounded body like this, not very sharp. This shock is going to be a detached shock, it will be located ahead of the body.

And if you bring in a pitot-tube there is going to be a detached shock in the front. So, the probe stagnation pressure is going to be more than that of the free stream. Because behind a shock there is going to be an increase in the pressure because of the shock. This is the phenomenon of shock wave, this is the feature of a shock wave that the stagnation pressure increases. So, that means the reading will be wrong because now you are not reading the free stream pressure. You are reading the pressure behind the shock which will happen because the flow is supersonic.

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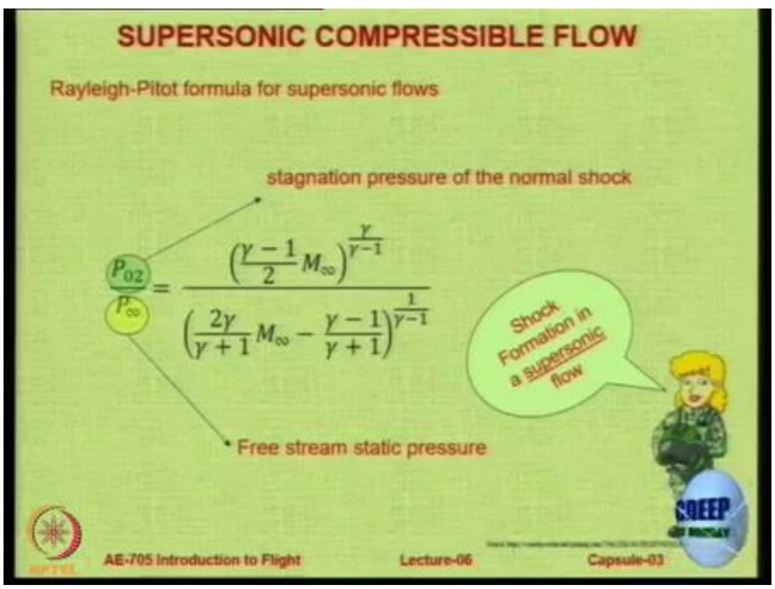

So, there is a Rayleigh-pitot formula for supersonic flows through which we can get this expression. We are not going to either prove it or nor we are going to derive this expression that is not a part of this course or introduction to flight just I want to tell you, that the ratio of pressures is different in compressible flow, compressible flow without shocks and compressible flow in supersonic flow. So let us see now you do not believe me I would like to show you a show but before that there is a question, yes?

Professor: Total pressure, what happens to that, it remains constant.

Student: Total pressure.

Professor: So, what will happen to the readings.

Professor: Yeah you are right, you are right, you are right. Static pressure is going to increase so, the pressure that the probe is facing will be different from what is the free stream pressure and that will lead to the errors. So, thank you for correcting my mistake. You are right. Ok, let us see, let us see a small video that shows the creation of a shock.

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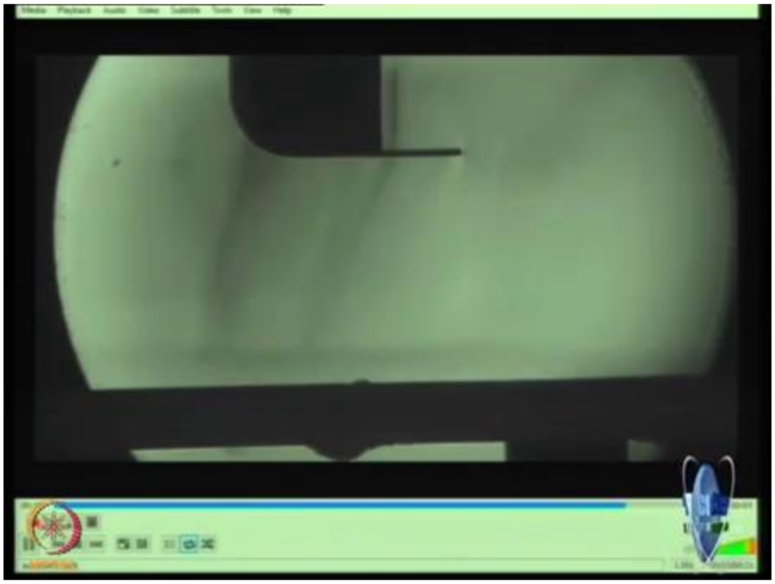

In a pitot-static tube, you can see as the flow becomes sonic, there is this very beautiful pattern formed and hence the pressure sensed by the tube is going to be behind this shock, it is not going to be the same. So there is a shock right in the front, there is a shock here, here there is a shock, here also. So, hence, what you get is not correct pressure.

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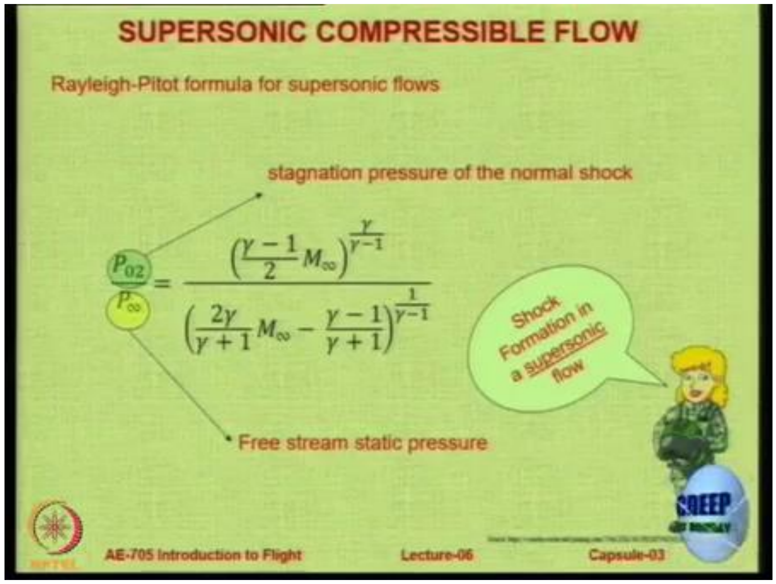

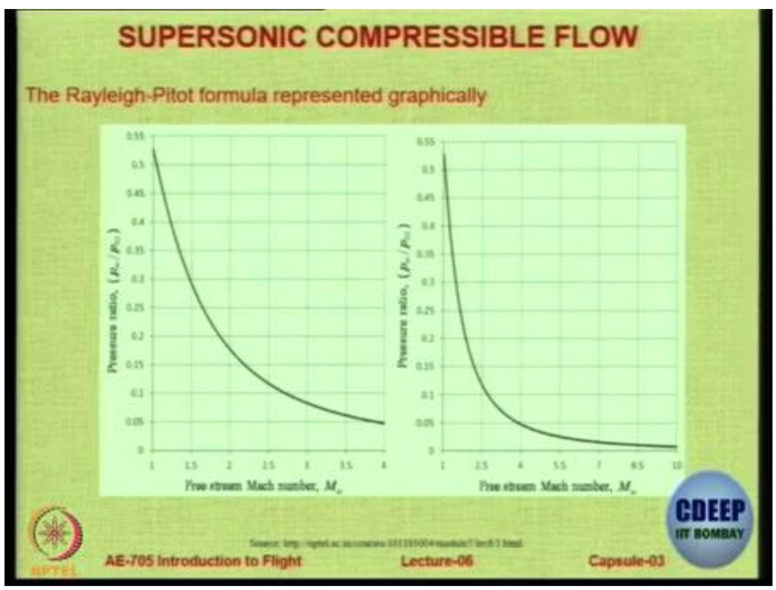

So these are some lines which tell you about the ratio in the pressure as a function of a free stream Mach number the first one shows only when the mach number is from 1 to 4, it is a zoomed in figure of this one which shows from mach number 1 to 10. So, you can see that there is a substantial drop. The pressure will be only ten percent of the free stream. If the mach number is approximately 2.7 or 2.6

And if you go to mach number 10, it is going to be very, very small as a ratio. So, this a Rayleigh-pitot formula which is coded in the pitots tube.

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But I want you to see this is a kind of shape that you will see for a pitot-static tube used on all aircraft which go faster than speed of sound. In supersonic flow, so there will be a center symmetry axis and there will be a bulbous nose in the front and there will also be something on the back; So, the question is, why are the pitot tubes shaped like this in case of supersonic aircraft?

So, the answer is that we need to compensate the position error or the error which is coming because of its position and also because of the presence of shocks. So let us see how it works.

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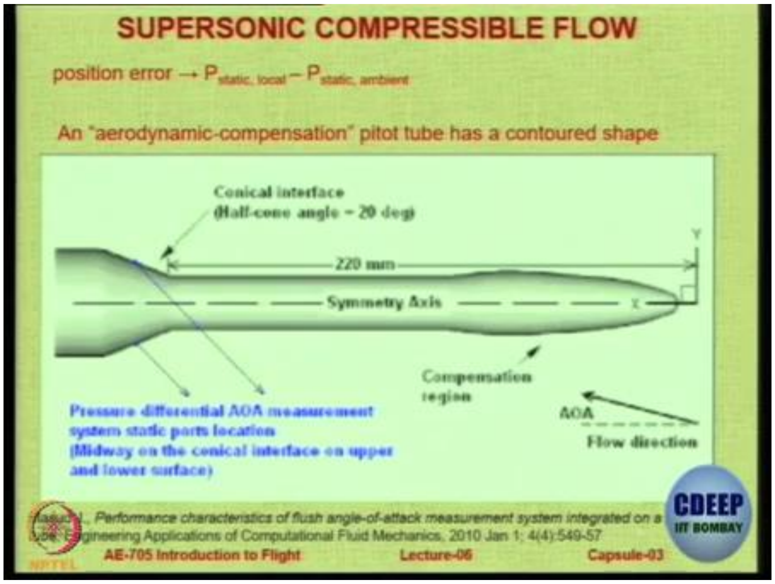

So basically what is position error? The position error is that the static pressure locally is not same as ambient. And the difference between them is a called as the loss in static pressure which leads to an error called as a position error.

So, that means you have to give some kind of a aerodynamic compensation for the shape of the pitot-static tube or the pitot tube so that it reads the correct value of pressure. So this is that particular compensation region which is in the front. And on the back you also have another conical area which is again meant for the same kind of compensation, but now there is another interesting thing. What you can do is you can mount some, sensors, in this area and in this area.

And the difference in the pressure that you record in the upper and the lower surface. You can use it for finding the angle of attack of the aircraft, or the angle at which the probe is mounted to the flow. So this particular figure has been borrowed from a paper which has been published by a faculty member from a university in Pakistan, Professor Masood. He has done some CFD investigations, and we have borrowed this particular figure from the paper.

The journal is called as the 'Engineering Applications of Computational Fluid Mechanics' and as you can see in the next slide.

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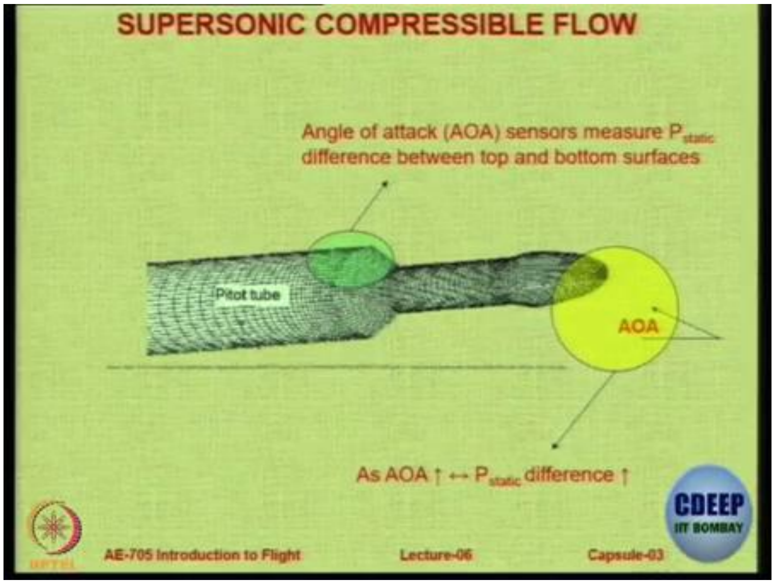

This is the mesh that was created across the pitot-static tube. And the angle of attack sensors mounted, they measure the static differences between the top and bottom surfaces, and with that. So, as the angle of attack increases, then, there is an increase in the static pressure difference. Because of the angle of the pitot-static tube.

And that difference in static pressure can be communicated with the pilot as an indication of at what angle of attack the pitot tube is facing. Now, this has to be corrected to the aircraft angle of attack, that is a different matter. But you can use the pitot-static tube to calculate at what angle the aircraft is pointing to the free stream. This is not possible with subsonic flow; because in subsonic flow you do not get these kind of differences in static pressures at an change in the angle; it happens only in the supersonic flow because of the presence of the shock waves.

So, there will be a shock wave there at the corner. So, this kind of a pitot-static tube or this kind of a system is very commonly employed in supersonic fighter aircraft. So, on the moodle page you can actually show us the photographs of such tubes for some typical fighter aircraft which fly at very high speeds, just to increase our appreciation. So, now the last thing I want to talk to you, as far as the pneumatic measurements are concerned, is the air data module.

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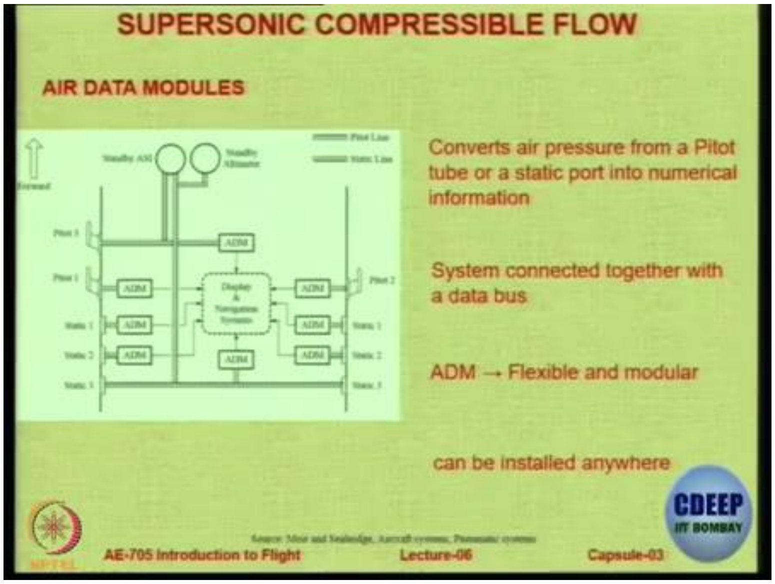

The air data module is essentially a system by which the pressure information, measured by pneumatic instruments is converted into digital data. So that the onboard systems like the fly-by-wire system or any other system are able to use it. So, basically what does ADM do? ADM converts the air pressure from a pitot tube or a static port into numerical information. And this particular system is then connected together electronically by a data bus. So, as you can see in this example, there are 3 pitot tubes, 2 are on the left hand side; pitot tube number 1 and 3 and one on the right hand side.

And you have 3 static ports on the left and 3 on the right; and you will notice that all of them are coupled together, so that the average value can be taken. So, for on each of these particular probes you have an ADM system attached which converts the pneumatic reading into digital reading, and then it sends it to the display and navigation system in the center. But, you can notice that there is a standby air speed indicator and a standby altimeter, which may not be connected to this particular system; this is just a backup system.

Because in case, electronics fail, then the manual backup for the pilot is needed for these 2 primary instruments. So, it is a very flexible system, it is a modular system, you can plug in and use it; and this is very commonly found in most modern aircraft. Because most modern aircraft are using electronic systems, for the display and navigation of the aircraft, ok, right. So, yes.

Professor: That is a very good question. I was waiting for it to be asked at that time, but sometimes processing takes time. So, he has been processing the information and now he comes at this question. Can somebody answer this question?

Professor: Ok, very good! I am happy to see that M.Tech students also think a lot, yes? Yes, what is it? Do you have any thought about it? So, can anybody else try to answer this question? Only one tube is blocked, why not the others? So, for this I would request you actually spend some time, and read the reports which are given online. There are crash investigation reports about this aircraft. As I said this is one of the first time, when we had such a fatal failure of an aircraft because of the blockages.

So, no, no need to guess your answer right now, we are not playing a guessing game. We will, we will use moodle page to educate ourselves. So, I would encourage people to first of all if somebody can download the crash report and upload it on the moodle page, that will be great. If someone can go through the main observations and then answer this question, 'If one of the static ports is blocked, why should the whole system fail?'

Do you have a question?

Student: I can guess but as you said guesses are not allowed…

Professor: Yeah, I mean, guesses are allowed but not welcome; because see there are times when we want people to guess, because an intelligent guess is also very interesting. But you know we will see simply, we will simply keep guessing this may have happened, instead of that, this is a historical fact. Data is available, let us read it and let us educate ourselves.