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Aerospace Propulsion
General Performance Parameters I
Lecture 8

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Good morning, in this class we will discuss what is the role of efficiency that is propulsive efficiency as well as well as the overall efficiency for both are breathing and non air breathing engines, okay. But before we do go there I just wanted to ask you this question let us say we use a rocket motor inside water for a torpedo is it going to be useful or do you think it is not going to be very effective what is your opinion for an underwater torpedo, if you are looking at using a rocket motor operators usually have a propeller driven system.

If we use a torpedo with a rocket engine instead do you think it is going to be very effective or not going to be effective, which are not effective okay, let us see as we go along in this class what is the reasons and what whether it is going to be effective or not, okay. Now firstly just to recollect that if you are looking at a aircraft engine you can consider it as a box air breathing engine.

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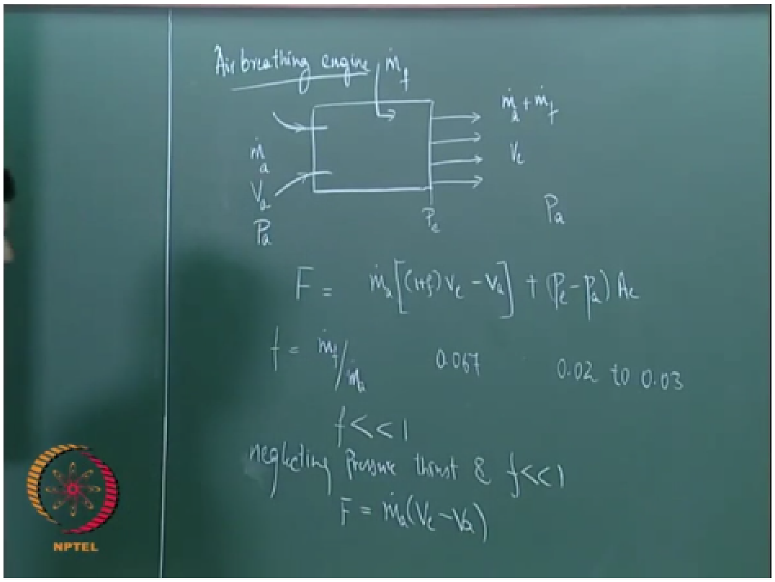

You can consider it as a box wherein you are in putting certain mass flow rate of fuel and certain mass flow rate of air comes in through the inlet at ṁa, a va and pa and this goes out the mass flow-rate is ṁa+ṁf and ve be the velocity and let Pe be the pressure here and ambient pressure be Pa, now we know that the thrust of this air breathing engine would be ṁa[(1+f)ve-va] okay.

Now f is nothing but ratio of mass flow rate of fuel to mass flow rate of air typically for aircraft engines we have seen this for stoichiometric it is around 0.067 but usually we operate it less than that so it is around going to be around 0.02 to 0.03, so f is we can make an assumption that f is very much less than 1 and therefore neglect this part, neglecting this part the error is typically of the order of 2 to 3% only okay.

So if we neglect this part and if we also neglect the pressure thrust component which is usually small in aircraft engines, so neglecting pressure thrust and using f being very much less than one we get f=ṁa(ve-va) as the thrust equation, this is the thrust equation that we are going to use in this class for all the further calculations that we do.

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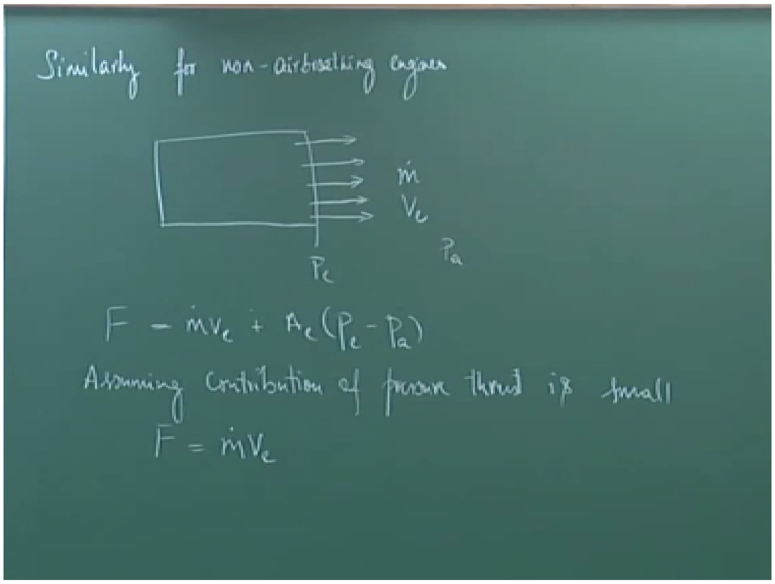

And similarly for rockets for non air breathing engines we can assume this is a box right where the pressure at this point is Pe, ambient pressure is Pa and ṁ is the mass flow rate and v is the velocity. Remember rocket motor or a non air breathing engine carries its own fuel and oxidizer therefore it does not depend on air flow through it okay, and there is no intake as such okay.

All the mass that is needed to be thrown out is generated inside the rocket motor itself, so here again thrust we had derived this expression before as ṁve+ Ae(Pe-Pa) right, now again if we assume that the contribution of rational trust is small then we can write thrust for a rocket motor as ṁve, okay. Now notice that ve is very similar to some other quantity that we had defined earlier all is right.

So we get this expression for thrust and this is the expression that we are going to use in this class for rocket motors this is the thrust and for air breathing engines this is the thrust that we are going to use okay, right. Now if you look at let us say we have this much of energy.

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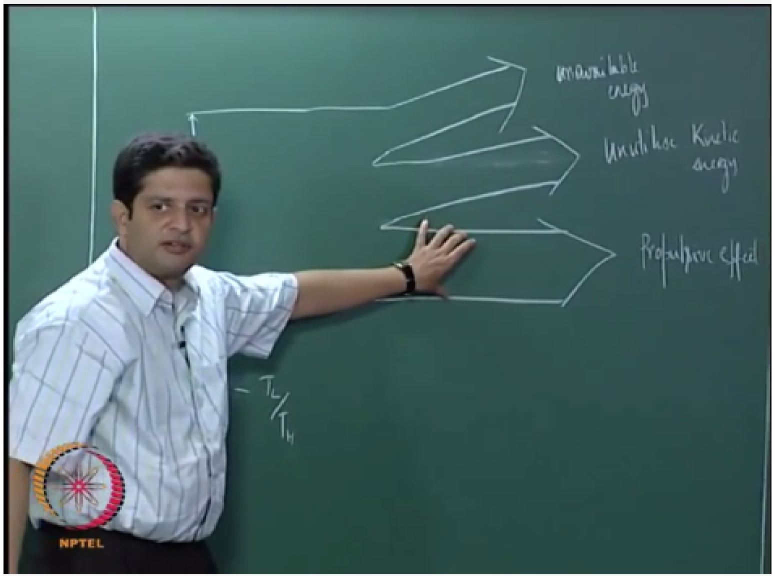

In a air breathing engine as well as in a non air breathing engine what we have is chemical energy stored in the propellant of the fear right, and that is converted into heat and then to kinetic energy right. So if we are going to look at efficiencies we have to consider what is the input energy, the input energy is the chemical energy that is stored in the in the fuel or propellants right.

Now a part of this not all of this chemical energy is going to be usefully converted only a part of it is going to be usefully converted to the power that we require or the thrust power that we call it at. Now you know from thermodynamics that you cannot have a system that can operate without with only one laser what right you need two reservoirs one high temperature reservoir and one low temperature reservoir and heat must be lost to a low temperature reservoir.

So here also we have to lose heat to a low temperature is our, so because of the cycle the particular cycle that we follow we are going to lose certain amount of energy due to this. Let me call this as unavailable energy okay, so this is because you have to lose heat to any cycle that you take even if you take Carnot cycle reversible Carnot cycle the efficiency cannot be one right, because you need to lose heat to a low temperature reservoir.

And therefore even if you look at the Carnot cycles you will have something like this Carnot cycle efficiency is η is given by η 1-TL/TH right, this is temperature of the loader temperature reservoir and this is the temperature of the high temperature reservoir, so it has to lose heat to a low temperature reservoir and therefore this cannot be 0 therefore you have efficiency is less than 1, so this component takes care of that.

Now all the remaining energy that is available cannot also be converted to useful propulsive power a part of it goes in the stream is lost in the stream as kinetic energy. Unutilized and only the remaining portion is the useful in producing the propulsive effective, okay. Now we will design define something known as thrust power.

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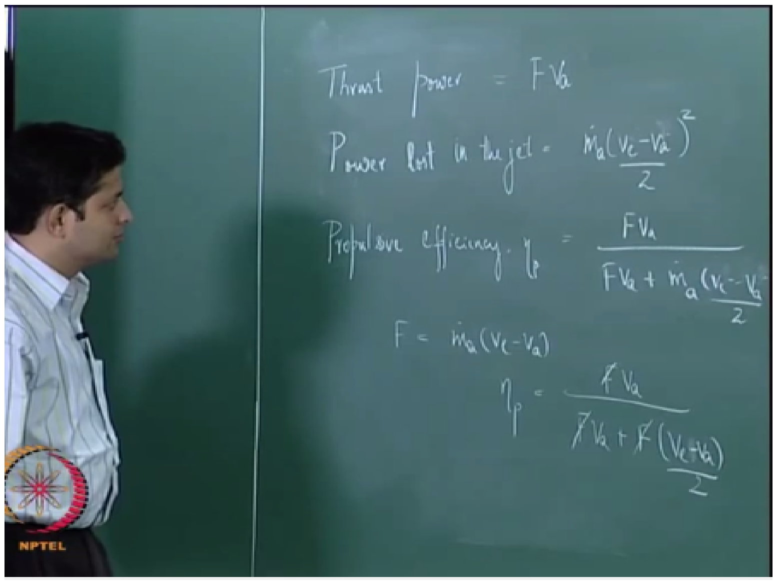

We will define something known as thrust power, thrust power is nothing but F Va okay, and this is the portion that we are talking about now what is the unutilized kinetic energy or the power lost in the jet that is given by mass flow rate $\dot{m}$a into right, this is the power lost in the jet. So if we are looking at defining something known as propulsive efficiency this will be propulsive efficiency will be nothing but this divided by this entire quantity okay, right.

So that is fVa/Fva+$\dot{m}$(va2-ve2)/2, so now how do we go about further simplifying this, we know that thrust is f is equal to nothing but $\dot{m}$a(ve-va), so we can use that here okay, ve - va is ve^2-va^2 we can use that as this is nothing but if I take out $\dot{m}$(ve –va) it will be ve + va/2 so I will get propulsive efficiency if I take this as right, okay. Now I can cancel out all the f, so if I cancel out all the F, I will be left with.

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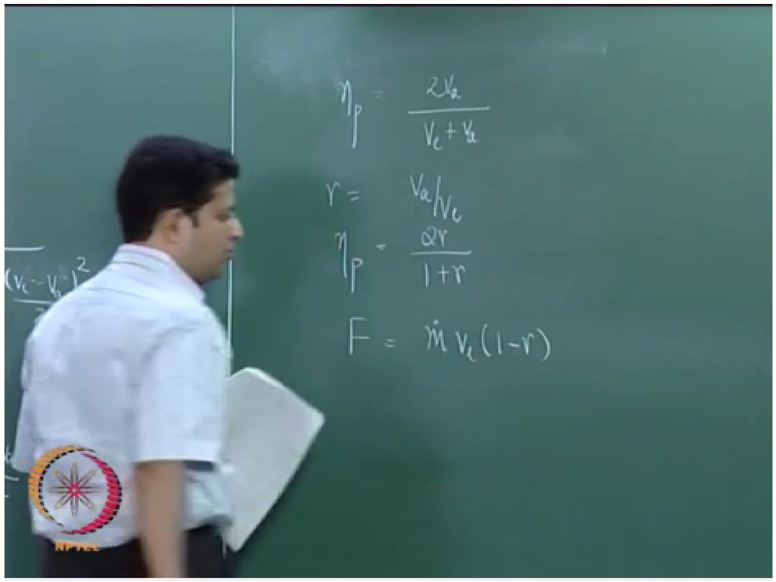

Propulsive efficiency is equal to 2va divided by, sorry there was a small mistake and you did not correctly, the power lost in the jet is not this $(ve-va)^2$ so if I take that into account I will get here if I take out this I will get this thing is to ve-va/2 okay, so now I will get ve+va I will define a ratio called R which is nothing but ratio of velocities given by va/ve I will define r which is ratio velocities and using this I will get if I put it propulsive efficiency in terms of r I will get 2r/1+r okay.

And similarly I can write thrust also in terms of r as F is nothing but $\dot{m}$ve(1-r) okay, now let us see how this varies with r, what will when will this be maximum then we will ηP be a maximum when r is 1 right, and r is 1 it will be a maximum and if you look at this expression here thrust will go to 0 when R is equal to 1, so let us plot that.

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This has to beam ṁave, so if I plot f/ṁa ve and ηP on the same axis y axis versus r, how does ηP very let us say this is r=0 this is r=1 and this is 1 here, so this is the variation of ηP what happens to f, f is as r keeps on increasing f decreases so you get a straight line and it goes to 0 at this point okay, so this is the variation of so if we go beyond r of 1 then the thrust produced will become negative and therefore has no meaning, right.

It has no meaning beyond this point and r less than 1 is the regime that we are looking at and if you look at this r=1 it goes to 0, so we cannot be at this point we have to be somewhere here such that you have a sufficiently large thrust and your propulsive efficiency is also high okay. Now if you remember when we were discussing about turboprops I made a mention that turboprops are devices where in ṁa is increased when the velocity differential is reduced.

In order to get the same thrust you can do it two ways you can either increase ṁa or you can increase ve –va, if you increase ve-va then the propulsive efficiency goes down okay, so your turboprops will have higher propulsive efficiency because of this. So if you have r of around 0.44 you will get ηP around something like 74% okay, this is propulsive efficiency for aircraft engines let us look at what is the propulsive efficiency for rocket engines.
I do not think this is the right, number for aircraft engines and this is for rockets for aircrafts if F=70kN and ve=800 km/hr and ve= 1800km/hr possible because the nozzle is took at a higher temperature right, so you have higher speeds at the exit then you get a propulsive efficiency of around 61.5% with this okay. Okay, now let us look at what is the relationship for propulsive efficiency for rockets.

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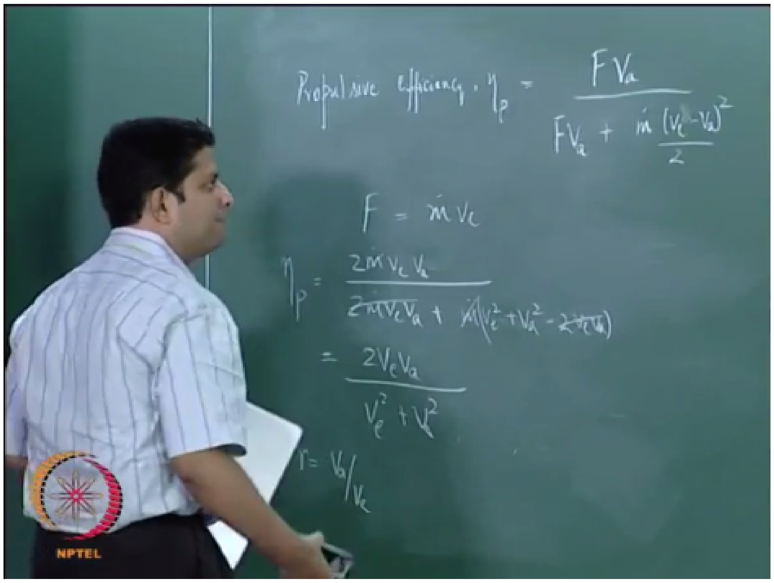

Now again for rockets propulsive efficiency is thrust into velocity that is thrust power divided by thrust power +kinetic energy lost in the jet okay, now here we know that F is a nothing but $\dot{m}$ve right, so if we substitute this expression here we get ηP=$\dot{m}$ ve va if I bring the 2 from the denominator here, divided by 2 $\dot{m}$ve v a + $\dot{m}$(ve^2+va^2)-2ve va okay.

Now this and this cancels outright to $\dot{m}$ve va with a minus sign and to $\dot{m}$ve va with a positive sign so these two will cancel out and you can also cancel $\dot{m}$. So you are left with ve^2+va^2 okay, and if we use the same definition for rs, R=va/ve okay.

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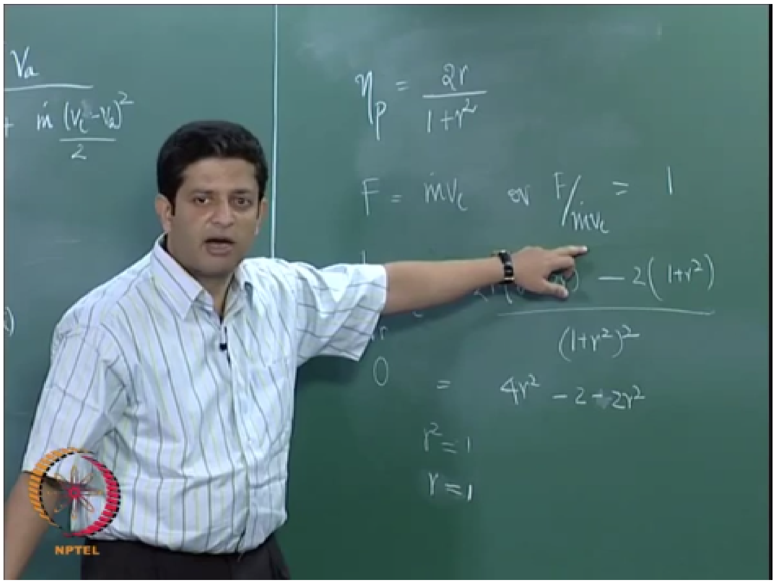

We will get $\eta P=2r/1+r^2$ and similarly if I were to write f in terms of r I will get F is equal to there is no r right, it is independent of va so therefore it will not change right so this is one of the key parameters here the thrust of a rocket motor is independent of the ambient velocity or the velocity of the vehicle okay. So you get ṁve or f/ṁve is always 1 irrespective of whatever is the velocity va that it is traveling at it still continues to produce thrust.

Whereas in an aircraft engine or an air breathing engine you saw that if the velocity ratio was greater than 1 then the thrust produced would go to negative values or it could mean that there is a drag on the vehicle right, here it is independent of it and it always this quantity is always 1 okay. Now where will this be a maximum propulsive efficiency how do you determine that well very simple just differentiate with respect to r you will get $2r(0+2r-2)1+r^2/(1+r^2)^2$ this is nothing but $4r^2- 2- 2r^2$.

So what should go to 0 for this to be a Maxima the derivative must go to maximum or minimum the derivative must go to 0 so if you put this to 0 you will get the value of r that is $r^2=1$ or r =1 is the value how do we know that this is a Maxima you take a second derivative right, that should be if it is a maximum what should be the second derivative should be negative if you take a second derivative this would be what will this be okay, find that out.

Now r is 1 and notice in the earlier case are equal to 1 we got thrust 0 for air-breathing case now for rockets it will still be f by ṁve would be still 1, so it is independent of the ambient velocities or the vehicle velocities. So if I plot it on a different colored chalk.

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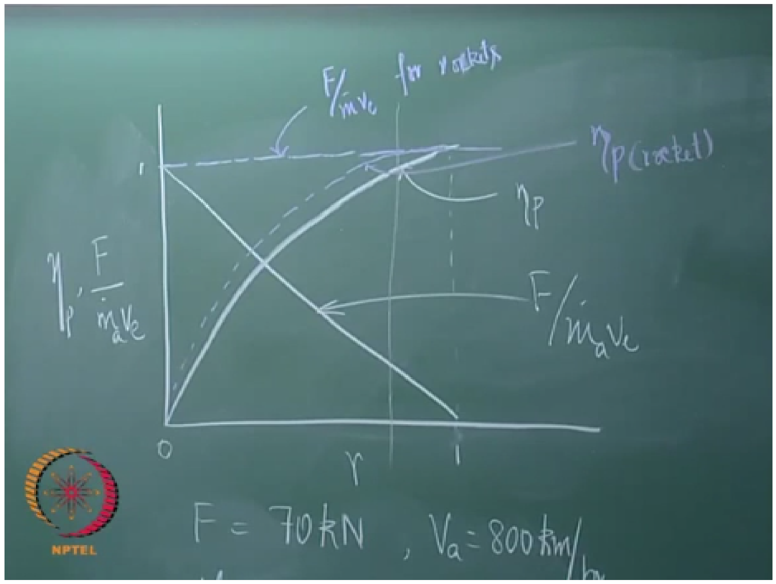

And right, so propulsive efficiency is for rockets are typically slightly higher than that of everything engines because of the term $1+r^2$ here if you remember it was 1+r for air breathing engines r being less than 1 it will always this term will be smaller compared to 1+r therefore you will find propulsive efficiency spur Rockets will be slightly higher than those for everything engines.

So propulsive efficiency is higher why should not we use rockets as the question we will try to look at okay, now coming back to the question that I asked you right at the beginning suppose we were to use a rocket motor to run torpedo whether that would be useful or to take the exhaust from the rocket motor run a turbine and connect that turbine to the propeller and let the propeller do the work on the fluid would that be used okay, let us see that.

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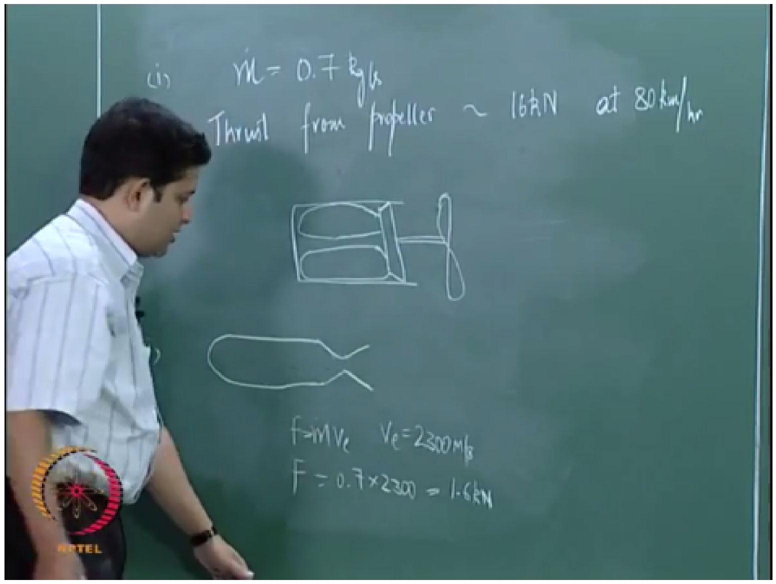

Now let us assume the mass flow rate ṁ to be around 0.7 kg/s now if this were to make this were used as a gas generator and made to power propeller the thrust produced would be typically something like would be around 16kN at something like 80 km/hr. Remember water is you are looking at a torpedo and water is what kind of a fluid incompressible fluid right, or compressibility effects are very, very small.

You need to go to very high velocities in order to get to that right, so we would be typically operating at very low velocities here. So now this is the thrust that is produced if it is if this kind of flow rate is given to a propeller now let us say we were not doing that and we were giving we were directly throwing out the exhaust this is the situation wherein you have a gas generator or a combustor here and this is made to run a turbine, turbine is connected to a propeller and the propeller powers the vehicle forward, okay.

Now instead of this you can also operate for another system wherein it is just like a rocket motor just only the combustor and you have a CD nozzle right, let me call this situation 1 and I will call this situation 2 here if I have the same mass flow rate going through just a convergent divergent nozzle I will get a thrust this depends on exit velocities for a rocket motor if you remember it depends on exit velocities ve.

So f is nothing but ṁve in this case ve is around 2300m/s so I get a thrust of 0.7 into that is somewhere around 1.6kN okay, look at this number is 1/10th of this right, how did this happen, the answer lies again in propulsive efficiency if you look at the r and propulsive efficiency. if you look at the R into propulsive efficiency for the two situations for this one the actual va would be something like 22m/s okay.

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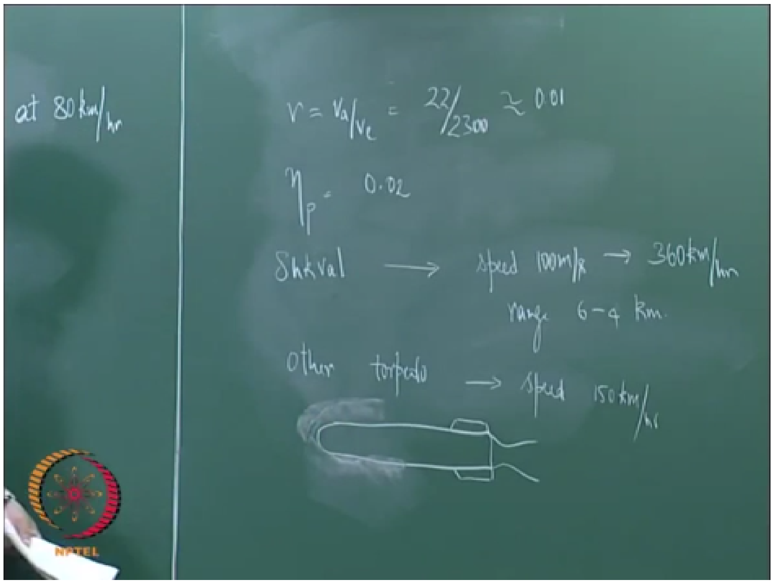

So you take R as va/ve that is 22/2300 around 0.01 and if you calculate propulsive efficiency you will get ηP=0.02 so most of the thrust or most of the useful power here is lost in the as the kinetic energy of the exhaust gasses okay, it is not used usefully so it will always be better if you do this propulsive efficiency wise. So if you were to make a statement from based on this you will say that it would be ridiculous to use rockets for hospitals right.

But Russians do have a top-secret torpedo that they call as squall it is pronounced as squall which uses a rocket motor and therefore it goes at a speed of 100m/s or 360km/h and it is range is something like 6 to 4km very short range right, and it goes very fast the other torpedoes comparable ones are something like have a very small velocity is compared to this torpedo speeds are of the order of less than half of this okay, this is because the other torpedoes use the first kind of mode and a squall uses this kind so it can go at a very high velocity.

But remember if you go at very high velocities they drag inside water will be enormous so they use something known as super cavitating flow wherein they produce gas bubbles in front of the vehicle, if this is the vehicle it is the vehicle and this is the exhaust they produce they have a gas bubble generator and produce gas bubbles all over this place right, in front of it so that the drag on the vehicle is less because now you are looking at something like a two-phase flow it is not pure water so the viscous drag will reduce and therefore they can make this kind of velocities right.

Otherwise typically you do not find anybody using scenario 2 to power a torpedo because a lot of useful power is lost and only the kinetic energy of the jet okay. Now let us move on and look at what is the overall efficiency okay.

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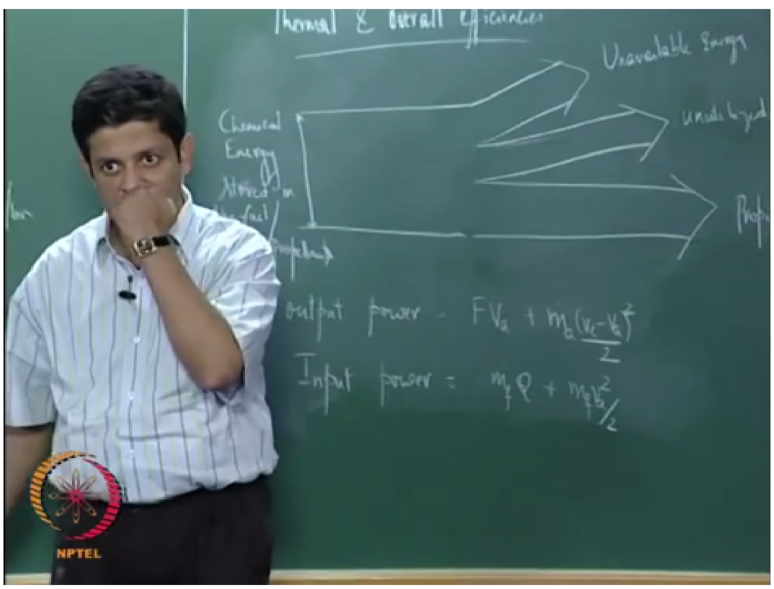

Look at again going back to our figure this was unavailable energy and you had unutilized kinetic energy and lastly you had the propulsive effect right, in this was chemical energy stored in the fuel or propane okay, so if I went to calculate thermal efficiency what should I look at what is thermal efficiency here propulsive efficiency was this quantity divided by this quantity so similarly what is thermal efficiency.

Thermal efficiency is if you take output power as Fva that is this part plus this part and you divide it by this one right, this gives you the thermal efficiency remember I also earlier mentioned about Carnot cycle efficiencies and why this losses there right. So and the chemical energy stored in fearless or the input power is ṁfQ right, this is this portion and we are looking at this portion right. But in addition to this we also need to add one more term there is a power that is required to carry or transport the fuel remember these are flying systems and they cannot be powered like systems on ground they have to be lifted up and carried along with the vehicle.

So there is a power that needs to be added to this and that is ṁF $va^2/2$ this quantity is small if you look at aircraft engines compared to the compared to this, this is small for aircraft engines but it is really not small in terms of rocket engines this quantity will be large for rocket engines. So from this we can find that thermal efficiency okay.

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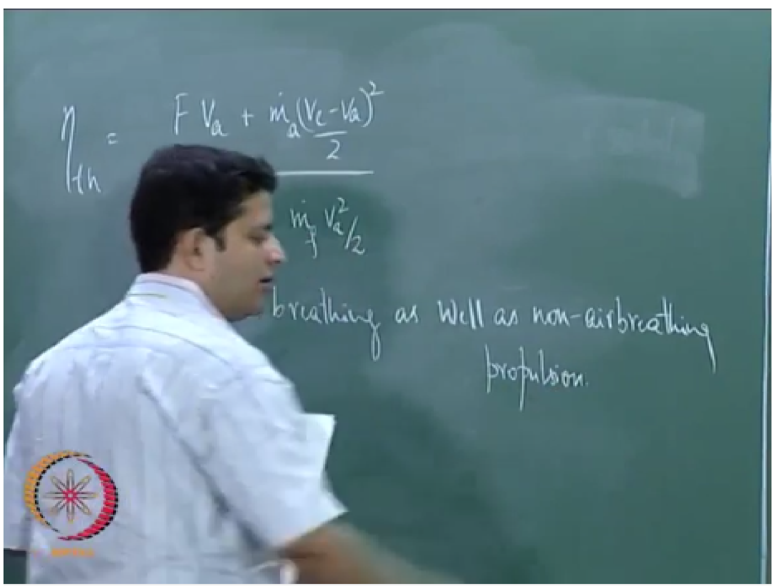

Thermal efficiencies F va+ ṁa right, this is the expression for thermal efficiency right, and this expression holds for both aircraft and for air breathing as well as non air breathing propulsion. We will stop here in the next class we will look at what is the overall efficiency and what role does it play in terms of the range of the aircraft and other things, okay we will stop here, thank you.

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