Course Name: Engine System and Performance
Professor Name: Pranab Kumar Mondal
Department Name: Mechanical engineering
Institute Name: Indian Institute of Technology, Guwahati
Week - 10
Lecture – 40

Lec 40: Numerical Problems on Turbocharger

I welcome you all to the session on Engine System and Performance, and today we shall solve one numerical problem on turbochargers. In the last class, we discussed turbochargers. We saw the operation of a turbocharger. As such, we discussed the constructional features of the turbocharger unit and, of course, the advantages of this particular unit in the context of engine operation. We also identified problematic issues with this unit.

So today, we shall solve a numerical problem, and the problem is essentially about turbochargers. If I recall correctly, in the last class, we solved one numerical problem on superchargers. So, the basic difference between these two units is a supercharger essentially has one centrifugal compressor, and then, depending upon the requirement, there may be an aftercooler installed at the exit of the compressor because, the compressed air will have a high temperature. The temperature of the air will increase in the subsequent stages.

That high temperature may lead to detonation or knock in SI engines. But a rise in temperature may not be problematic, or rather a problematic issue, for CI engines. So, in a supercharger, the compressor is driven by consuming or borrowing a certain amount of power from the engine shaft, while in a turbocharger or turbocharging unit, the compressor is driven by a small turbine, and the turbine is rotated by the exhaust gases. To be precise, by exploiting the kinetic energy of the exhaust gases. The most important difference between these two units—supercharger and compressor—typically, this compressor is a centrifugal compressor, driven by the energy of the engine, which is available at its output shaft, while for the turbocharger or turbochargers, the small compressor is driven by a small turbine, and the turbine is driven or operated by the exhaust gases. So, this is the fundamental difference between these two units.

Certainly, you can understand that if we can really use the energy, which would otherwise be lost by the exhaust gases to the ambiance. To drive a small turbine, and if we can connect the compressor—or rather, if we can have one common spindle and if both rotating elements, which are rotating devices, are connected to a common shaft—then the compressor can be driven. So, for this case, you can see what is available at its output shaft. So, a certain amount of output power will again be used to run the compressor. So, we need to compromise with the engine efficiency.

So now, let us solve the numerical problem as such. We have solved one numerical problem on superchargers in our previous class, but today, the sole objective of solving this problem is to get acquainted with the performance map. So, this is basically the performance map of the compressor.

Problem 1: A naturally aspirated four-cylinder, four-stroke engine has the following specifications: Total displacement volume is 2316 cm^3; compression ratio is given as 9.5, and it produces a BHP of 83 kW at 90 RPS. For this naturally aspirated engine, inlet manifold conditions are 1 bar and 310 K; volumetric efficiency is 84%, and the mechanical efficiency is 90%. A turbo-charged version of the engine utilizes a compressor whose performance map is shown in the following figure. Estimate the brake power of the turbocharged engine at 90 RPS, if the compressor pressure ratio, P_2/P_1 is 1.5. The compressor is followed by an after cooler and its exit temperature is 340 K. Volumetric efficiency is 91% and mechanical efficiency is 88%. Assume that the net indicated power is proportional to the flow rate i.e.

$$\frac{imep_{TC}}{imep_{NA}} = \frac{\left(\frac{\eta_v P_i}{T_i}\right)_{TC}}{\left(\frac{\eta_v P_1}{T_1}\right)_{NA}}$$

What is the compressor speed and its efficiency? What is the heat transfer to the intercooler?

Solution:

So, the engine is a four-stroke cycle engine and four-cylinder. For this naturally aspirated engine, the inlet manifold conditions are 1 bar and 310 K. So, that means when the engine is naturally aspirated, there is no supercharger or turbocharger. So, the ambient conditions are 1 bar and 310 K. Essentially, the volumetric efficiency and mechanical efficiency are the efficiencies when the engine is naturally aspirated. This is the performance map of the compressor, and the compressor is now part of the turbocharging unit. So, essentially by this time that compressor is used to raise the pressure. So, the pressure ratio is very important parameter for the design of compressor. And the pressure ratio is given P_2/P_1 equal to 1.5. Otherwise, it will lead to another problem that is knock because probably the engine is SI engine from the statement you can understand. It is not universal, but true that after cooler will not be there for the CI engines. Typically, for the SI engines, after cooler is a must, but for the CI engines, depending on the requirement, after cooler may be there. So, the compressor is followed by an upper cooler and its exit temperature is 340 K. So, essentially, when the engine is not a naturally aspirated engine, that the engine is turbocharged, the same engine is giving volumetric efficiency 91% and mechanical efficiency 88%. So, you can understand, little bit increases the volumetric efficiency that is what is the objective of having this unit. So, the amount of mass or the mass that should be consumed by the engine during intake stroke or greater mass of or greater amount of air can be drawn into the engine cylinder that is why this turbocharging unit is there. Now, assume that the net indicated power is proportional to the flow rate and that is given by relation. So, we will be using this. The first part is basically we need to estimate the brake power of the turbocharged unit. The second part is to estimate the compressor speed and its efficiency.

So, all these things are very important to know. Let us now solve the problem, if we start solving the problem, let us start from here.

So, we can see that for the Naturally aspirated engine (NA) and the turbocharged engine (TC). So, these two we will be using for the naturally aspirated engine indicated horsepower, that is, brake horsepower by indicated horsepower is the mechanical efficiency. That equals,

$$\mathrm{IHP_{NA}} = \frac{83}{0.9} = 92.22\ \mathrm{kW}$$

So, that is the indicated horsepower for the naturally aspirated engine. So, from here we know BHP of the naturally aspirated engine equals to 83 kW. We have calculated IHP. From there, we can easily calculate FHP of the naturally aspirated engine equal to IHP minus BHP for the naturally aspirated engine. And if we calculate it, it comes as 9.22 kilowatt. So, you can understand 9.22 kilowatt, it is getting lost due to the frictional effect.

So, for the next slide, let me mention here for the turbocharged engine, volumetric efficiency is 91%, that is estimated, and mechanical efficiency is 88%. Certainly, we can see that when the engine is turbocharged, volumetric efficiency increases, though we need to or we need to compromise with the mechanical efficiency because mechanical efficiency has reduced by 2%.

So, if we go to the next slide, then we can write for the turbocharged engine, volumetric efficiency is 91%, that is 0.91 and this inlet pressure is what we need to know from the problem statement itself. For the turbocharged engine, the manifold conditions—that is, the air temperature and air pressure at the inlet manifold—will be dictated by the exit condition of the compressor. Though there is an intercooler, we can understand the compressor pressure ratio is 1.5. Certainly, if the ambient pressure is 1 bar, then the pressure at the exit of the compressor will be 1.5 bar and that is the manifold condition for the turbocharged engine. So, for the turbocharged engine, this inlet pressure equals 1.5 bar, and T_i is given. The compressor is followed by an aftercooler, and the exit temperature is 340 K. The exit temperature of air—or air temperature at the exit of the compressor—is equal to the air temperature at the inlet of the engine. So that is 340 K. So, given this data, what we can do—this is for the turbocharged engine.

Now, for the naturally aspirated engine, we can write volumetric efficiency equal to 84%, P_i equal to 1 bar, and T_i equal to 310 K. So, these are the statements. So, for the naturally aspirated engine, the inlet manifold conditions are these: volumetric efficiency 84% and mechanical efficiency 90%. So, these are the data given.

Now, it is given that the most important part of this problem is to follow this line. The net indicated power is proportional to the flow rate, and that is mathematically described by this relation.

$$\frac{imep_{TC}}{imep_{NA}} = \frac{\left(\frac{\eta_v P_i}{T_i}\right)_{TC}}{\left(\frac{\eta_v P_1}{T_1}\right)_{NA}}$$

So, this is nothing but the mass flow rate. So, we know all these quantities because for the turbocharged, we know η_v equals 0.91 and P_i equals 1.5 bar. Then, this T_i for the naturally aspirated engine will go up. So, it is 310 bar. Then, it is coming as 0.84 into pressure is 1 bar into this is 340 and the ratio, if we calculate, you will get it as 1.481. So, this is the ratio of indicated mean effective pressure for the two engines. If we go to the next slide, that indicated horsepower is proportional to indicated mean effective pressure. So, the work done on the piston by the gas is essentially dependent on the indicated mean effective pressure.

So, if this is the case, then IHP for turbocharged to IHP of naturally aspirated equal to 1.481 because this would be $imep_{TC}/imep_{NA}$, and the ratio already calculated is 1.481. From there, we can calculate the indicated horsepower for the turbocharged engine, which is 1.481 multiplied by if we go to the previous slide, we have already calculated the indicated horsepower for the naturally aspirated engine as 92.22 kilowatt. So, if we go to the next slide, we can simply write 92.22 kilowatt, and the answer is 136.63 kilowatt, which is the indicated horsepower of the turbocharged engine. It is given—let me again go back to the problem statement. It is given that even when the engine is turbocharged, the engine speed is 90 rps. So, the engine speed is not changing. Essentially, this line gives us a clue that the frictional horsepower will remain unaffected. Since the speed remains constant at 90 rps, the frictional horsepower is the same for both conditions. So, that means we can easily calculate the brake horsepower for the turbocharged engine. It is, this IHP of the turbocharged unit multiplied by mechanical efficiency. Because brake horsepower divided by indicated horsepower is the mechanical efficiency.

So, this is nothing, but if we write this as 136.63 and mechanical efficiency is 88%, that is 0.88 kW. And if we calculate it, the value comes as 120.23 kW. So, this is the brake horsepower. Let me go back to the problem statement once again. The first part of this question was, to calculate or estimate the brake power of the turbocharged engine at 90 rps, which we already estimated. This is the first part, so that is, 120.23 kW. That is the answer for the first part. Had we considered, maybe frictional losses—because both of them are at the same speed—we did not take into account the frictional losses. That would, may even affect the brake horsepower for the turbocharged engine. But the good thing is that the speed remains the same. So, if we go to the next slide, next, we will have to determine the mass flow rate of air for the turbocharged engine. The sole objective is to equip or install this particular unit to increase the mass flow rate. So basically, a greater amount of mass can be consumed.

So, if we need to take this, what we need to do is calculate the inlet air density. So, inlet air density—we have to calculate first—and that inlet air density, ρ_i, for the turbocharged condition, that is

$$\rho_{i|_{TC}} = \frac{P_i}{RT_i} = \frac{1.5 \times 10^5}{287 \times 340} = 1.537 \text{ kg/m}^3$$

This is the density. So, knowing the density, we can calculate the mass flow rate of air for the turbocharged case m dot a for the turbocharged case that would be equal to

$$\dot{m}_{a|_{TC}} = \rho_{i|_{TC}} \times V_{disp} \times \eta_v \times \frac{N}{2} = 1.537 \times 2316 \times 10^{-6} \times 0.91 \times \frac{90}{2} = 0.145 \text{ kg/s}$$

This is the mass flow rate. Now, let us refer to the compressor performance. So, now we will refer to compressor performance because, if we go to the problem statement once again, we can see we need to calculate compressor speed, efficiency, and finally, heat transfer to the intercooler. So, if we need to know the compressor speed, we need to use this performance map. Let me tell you the procedure of using this particular map to get some information about the compressor. So, if we go to the slide here. So, for the compressor performance, the pressure ratio of P_2/P_1 is the pressure ratio. That equals 1.5. So, do not be confused. 2 and 1 now: 2 is the exit state of the compressor or exit of the compressor, and subscript 1 is used to denote the state at the inlet of the compressor. So, P_2/P_1 equals 1.5, and essentially, we need to have this much flow rate to be handled by the compressor. So, the mass flow rate of air is again 0.145 kg per second. So, if we need to know something for the compressor, such as what should be the efficiency of the compressor, if we can use the performance map, it will make our calculation even easier. So, what we can do now is go back to the slide where the performance map is placed. By this time, we know the mass flow rate that the compressor will handle, which is 0.145 kg per second.

We also know the pressure ratio is 1.5. So, just if we use this color, the pressure ratio is 1.5, which is this line, and the mass flow rate is 0.145 kg per second, so probably it would be somewhere here. What do we need to do? We need to draw one line which is parallel to the pressure ratio, that is, the y-axis, but the line should pass through this particular point where the mass flow rate will be 1.145. So, if we draw a vertical line, it may not be exactly equal, but we need to draw a vertical line like this. And we also need to draw another Horizontal line, which will be parallel to the x-axis. And the line must pass through the point where the pressure ratio is 1.5. So again, if we draw another horizontal line like this, then these two lines will cut the isoefficiency line in this performance map. And from there, we can easily estimate the efficiency and then certainly the speed. So, all these are speeds, as you can see 1300, 1600, 1800, and these dotted lines are isoefficiency lines. Though we could not draw these two lines perfectly parallel to the y-axis and x-axis, what you need to do is exactly get the point where these two lines will cross the isoefficiency line. If we can identify that point on the isoefficiency lines, we can easily get the efficiency and speed of the compressor. So, for this particular case, we could not draw them properly here. You will be getting the isentropic efficiency of the compressor, which will be 70 percent, and the speed of the compressor will be 1650 rps. So, these two data points we will get from the performance map.

So, we have already mentioned, these are approximately, Otherwise, we have to use isentropic relations to calculate all this data. Now, having calculated all this, we can use the isentropic efficiency of the compressor is known, what we can do is we can calculate the exit air temperature at the exit of the compressor. So, let us use it. If we write that exit temperature is T_1 prime, then if the inlet temperature of air at the inlet of the compressor is T_i, then we can write this as P_1 by P_i power gamma minus 1 upon gamma. We can write this as

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 310 \times (1.5)^{\frac{1.4-1}{1.4}} = 348\ \mathrm{K}$$

So, this is basically the temperature of air or air temperature at the exit of the compressor. So, this is the answer of the problem, now this is the temperature of air at the exit of the compressor. But if we go to the next slide, if this is the compressor, then we will be having this is P_1 T_1, so this is P_2 T_2, so this is exit, that is inlet state, and this is compressor. But that air is not allowed to go to the engine directly; rather, it is allowed to go through an aftercooler or intercooler, and then this is the temperature, let us say T_2 prime, and that is the temperature of air which will be the inlet manifold temperature. So, the actual temperature, if we can write, the actual temperature of air at the inlet to the intercooler of the engine will be something different because, we have calculated T_2, but the actual temperature would be T_2 actual, because we have estimated T_2 assuming isentropic compression, but in a compressor, the actual compression process will not follow the isentropic one. So, if we try to calculate, so we know the isentropic efficiency of the compressor is nothing but, that is $T_{2a} - T_1$. So that is basically $T_2 - T_1$, and from there, we can calculate the actual temperature T_{2a}. That equals,

$$T_{2a} = T_1 + \frac{T_2 - T_1}{\eta_{ise,com}} = 310 + \frac{348 - 310}{0.7} = 364\ \mathrm{K}$$

This is basically the actual temperature at the inlet to the intercooler of the engine, hence from this we can say from this data heat rejected at the intercooler is

$$= \dot{m}_a C_{pa}(364 - 340) = 0.145 \times 1.005 \times 24 = 3.5\ \mathrm{kW}$$

So, this is the answer to the last part of this question. First, we have already calculated the brake power of the turbocharger. Then, we calculated the compressor speed, which is 1650 rps, using the performance map. We could calculate the isentropic efficiency of the compressor using the performance map, which is 70%. Finally, using the isentropic efficiency and the conditions of air before and after the compressor, we could calculate the amount of heat to be transferred to the intercooler. And the final answer is, that we have obtained 3.5 kW of heat to be rejected.

So, to summarize today's discussion, we can see that we have solved one numerical problem on the turbocharger. By solving this problem, we could, establish the theoretical or conceptual part related to this particular unit and this problem has helped me learn the use of the performance map for estimating isentropic efficiency and the speed of the compressor, knowing the pressure ratio and mass flow rate of air to be handled by the compressor.

So, with this, I will stop here today, and we shall continue our discussion in the next class.