Determining Displacement

5

5.1 The Engine as an Air Pump

Once a market need has been identified the first step in designing a new engine is to determine its required displacement. In this context the engine should be viewed as a positive displacement air pump. In order to produce the required work one must burn sufficient fuel. In order to completely react the fuel to products one must supply sufficient air. Determining the displacement required for a given engine is thus a matter of working backwards from the desired work output (or power at a given shaft speed), as further depicted in Fig. 5.1. Each of the steps in this process will now be covered in greater detail.

The first step in setting forth the expectations of a new engine is to determine the desired operating map. The characteristic operating maps for diesel and spark-ignition engines were discussed in Chap. 2, and various vehicular applications were reviewed. The needs of a particular application will define the maximum power required, and the rpm at which it should occur; the rate of torque rise as the rpm decreases from that of rated power; and the speed range between that of peak torque and that of peak power.

Once the full-load torque curve requirements have been determined the expected specific fuel consumption must be estimated. At the selected speed, the product of the specific fuel consumption, the desired power output at that speed, and the mass ratio of air to fuel provides the required air flow rate as shown in Eq. 5.1a and b.

$$\dot{m}_{fuel}\left[gm/hr\right] = \left(BSFC\left[gm/kW-hr\right]\right)\left(Power\left[kW\right]\right) \tag{5.1a}$$

$$\dot{m}_{air}\left[gm/hr\right] = \left(\dot{m}_{fuel}\left[gm/hr\right]\right)\left(Air/Fuel\right) \tag{5.1b}$$

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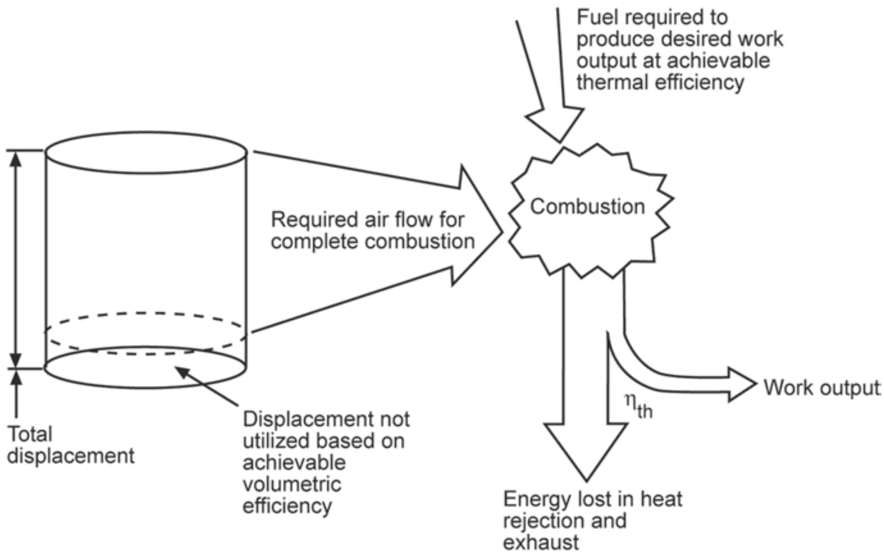

Fig. 5.1 Determining displacement based on combustion and output requirements

It will be important to ensure that both the rated and the peak torque conditions can be met, so the goal will be to determine air flow needs over the desired engine speed range.

As indicated in Fig. 5.2 the work output of the spark-ignition engine is limited by its displacement over its entire speed range. In contrast, the diesel engine is displacement-limited only at maximum torque, and may have an excess of air at higher engine speeds. Approximate air-to-fuel ratios for each engine are also indicated in Fig. 5.2. For the spark-ignition engine the chosen air-to-fuel ratio will typically be that resulting in maximum power or work output. This maximum occurs at an air-to-fuel ratio richer than that required for complete combustion—on the order of 11.5 to 12.5 to one for most liquid fuels. It should be briefly noted that for exhaust emission control (three-way catalyst operation) the air-to-fuel ratio in most engines is very closely controlled to its chemically correct mixture of approximately 15 to one under almost all operating conditions. Because the excursions to full load tend to be very brief the air-to-fuel ratio is almost invariably allowed to decrease in order to achieve maximum power, and in some cases to reduce full-load combustion temperatures.

The practical minimum air-to-fuel ratio attainable in diesel engines is leaner than that theoretically required for complete combustion. A minimum air-to-fuel ratio on the order of 20 to one is typical at maximum torque. The air-to-fuel ratio increase required at higher speeds is dependent on the desired torque curve and the turbocharger boost controls versus engine speed.

The next step in determining the displacement is to estimate the expected specific fuel consumption. If a new engine is being developed the engineer is not in a position to obtain measurements, but several resources are available to support this estimate. The first is to collect data from similar engines. Measurements could be made, or values could be

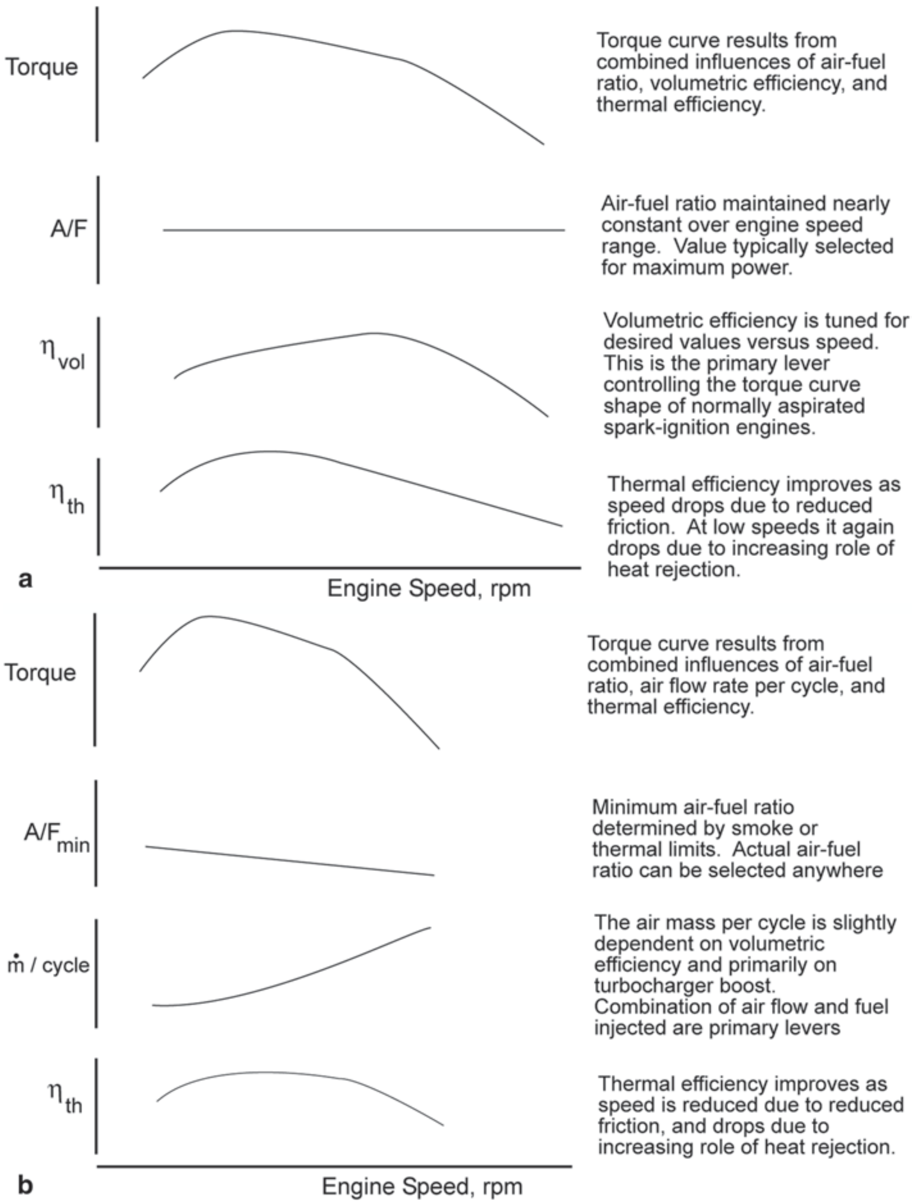

Fig. 5.2 **a** Variables defining the torque curve in the naturally-aspirated spark-ignition engine. **b** Variables defining the torque curve in the turbocharged diesel engine

obtained from the literature—technical publications will often be more reliable than marketing brochures for reported specific fuel consumption data. Another very good approach is to use an engine cycle simulation to model the planned engine. Several very well developed commercial codes are available that will provide close estimates. Beginning with validated models of similar production engines will add confidence to this calculation.

5.2 Estimating Displacement

Once the required air flow rate is known the displacement can be determined directly by looking at the engine as an air pump of fixed displacement operating at a particular speed. At any given rpm the displacement volume is filled with air every revolution in a two-stroke engine, or every second revolution in a four-stroke engine. The volumetric efficiency was defined in Chap. 1, and provides a measure of how well the displacement is utilized. Since the volumetric efficiency is the ratio of the actual mass flow of air inducted into the engine to the ideal rate based on completely filling the displacement volume, the actual displacement volume required in order to supply the needed air will be the ideal volume divided by the volumetric efficiency. A displacement rate can now be calculated by multiplying an engine's displacement by one half the engine speed (for a four-stroke engine), and then multiplying by volumetric efficiency:

$$Displ.\ Rate\left[liter/min\right] = \left(Displacement\left[liter\right]\right) * \left(\frac{N\left[rev/min\right]}{2\ rev/cycle}\right) * \eta_{vol} \tag{5.2}$$

By rearranging this equation and introducing the density to determine the mass per unit volume of air supplied to the engine one can calculate the displacement required to supply the necessary air flow rate at the given engine speed:

$$D\left[liter\right] = \left(\frac{\dot{m}_{air}\ kg}{min}\right) * \left(\frac{m^3}{\rho\ kg}\right) * \left(\frac{1000\ liter}{m^3}\right) * \left(\frac{\min}{N\ rev}\right) * \left(\frac{2\ rev}{cycle}\right) * \left(\frac{1}{\eta_{vol}}\right) \tag{5.3}$$

Several examples now demonstrate how the steps just covered can be used to estimate the displacement that will be required of a new engine. Attention turns first to a typical spark-ignition passenger car engine. The same approach will then be applied to assess the competitiveness of a diesel for the same application. Finally, the different assumptions required to size a heavy-duty diesel truck engine will be shown.

Spark-Ignition Automobile Engine The goal in this example is to design a new spark-ignition engine for an automobile application. The engine is to have a rated power of 100 kW at 5500 rpm. A literature study has suggested that the specific fuel consumption at rated power will be approximately 300 gm/kW-hr. Finally, a volumetric efficiency of 86 % at rated speed is assumed. The estimated displacement is calculated for these assumptions as:

$$\dot{m}_{fuel} = (100\ kW) * \left(\frac{300gm}{kW\text{-}hr}\right) * \left(\frac{kg}{1000gm}\right) * \left(\frac{hr}{60\ min}\right) = 0.5\,kg/min$$

$$\dot{m}_{air} = \dot{m}_{fuel} * A/F = (0.5\,kg/min) * (12.5) = 6.25\ kg/min$$

$$D\,[liter] = \left(\frac{6.25\ kg}{min}\right) * \left(\frac{m^3}{1.18\ kg}\right) * \left(\frac{1000\ liter}{m^3}\right) * \left(\frac{min}{5500\ rev}\right) * \left(\frac{2\ rev}{cycle}\right) * \left(\frac{1}{0.86}\right)$$

$$Displacement = 2.2\ liters$$

The predicted displacement of 2.2 L is quite reasonable for such an engine. Let us now assume that an engine is needed for a small sports car. The same rated power is required, but the engine will be designed to deliver this power at 7200 rpm. While the higher rpm will lead to an increase in specific fuel consumption this has been partially offset by designing the engine to run on a higher octane fuel, and increasing the compression ratio accordingly. The estimated specific fuel consumption is 320 gm/kW-hr. A tuned intake system and high performance camshaft are being designed, and the estimated resulting volumetric efficiency is 90 %. The predicted displacement is now:

$$\dot{m}_{air} = (100\ kW) * \left(\frac{320gm}{kW\text{-}hr}\right) * \left(\frac{kg}{1000gm}\right) * \left(\frac{hr}{60\ min}\right) * (12.5) = 6.67\,kg/min$$

$$D\,[liter] = \left(\frac{6.67\ kg}{min}\right) * \left(\frac{m^3}{1.18\ kg}\right) * \left(\frac{1000\ liter}{m^3}\right) * \left(\frac{min}{7200\ rev}\right) * \left(\frac{2\ rev}{cycle}\right) * \left(\frac{1}{0.90}\right)$$

$$Displacement = 1.7\ liters$$

It should be noted that especially in high performance applications the same calculations are often performed in the opposite direction. An engine of a certain displacement is given, and the objective is to maximize the power output. What rpm can be safely achieved? What can be done to the intake and exhaust systems to maximize the volumetric efficiency at that rpm? What other modifications can be made to minimize the specific fuel consumption (maximize the power output for a given quantity of fuel injected)?

Diesel Passenger Car Engine A diesel engine option is now to be offered in the same car considered in the first part of the preceding example. The same power is to be produced, but the final drive ratio must be selected differently, and the engine developed for a rated speed of 4200 rpm. The diesel engine will provide an inherent fuel economy advantage, so a specific fuel consumption of 260 gm/kW-hr is estimated. The lower engine speed of the diesel can be offset by its higher torque rise capabilities, and a 23 to one air-to-fuel ratio is selected at rated speed to allow margin for the desired torque rise at lower speeds. The slower speed should allow a higher volumetric efficiency to be achieved so a value of 91 % is chosen. The estimated displacement is:

$$\dot{m}_{fuel} = (100\ kW) * \left(\frac{260 gm}{\text{kW-hr}}\right) * \left(\frac{kg}{1000 gm}\right) * \left(\frac{hr}{60\ min}\right) = 0.43\, kg/min$$

$$\dot{m}_{air} = \dot{m}_{fuel} * A/F = (0.43\, kg/min) * (23) = 9.97\ kg/min$$

$$D\,[liter] = \left(\frac{9.97\ kg}{min}\right) * \left(\frac{m^3}{1.18\ kg}\right) * \left(\frac{1000\ liter}{m^3}\right) * \left(\frac{min}{4200\ rev}\right) * \left(\frac{2\ rev}{cycle}\right) * \left(\frac{1}{0.91}\right)$$

$$Displacement = 4.4\ liters$$

Unfortunately, under these assumptions the diesel engine will be twice as large as the gasoline engine designed for the same vehicle. This would certainly be unacceptable, and the power output would have to be reduced considerably (as was often the case in older, diesel powered automobiles). However, a very attractive option for the diesel engine is to add a turbocharger. If it is assumed that the incoming air can be compressed to 1.8 atm., and cooled back to 47 °C a further fuel efficiency improvement will be achieved as well. Assuming the specific fuel consumption can be reduced to 235 gm/kW-hr, and that all other parameters remain the same, the predicted displacement is now calculated as:

$$\dot{m}_{air} = (100\ kW) * \left(\frac{235 gm}{kW\text{-}hr}\right) * \left(\frac{kg}{1000 gm}\right) * \left(\frac{hr}{60\ min}\right) * (23) = 9.00\, kg/min$$

$$\rho_{port} = (1.8\ atm) * \left(\frac{1.01 \times 10^5\ N}{m^2 atm}\right) * \left(\frac{K}{287\ N\text{-}m}\right) * \left(\frac{1}{320\ K}\right) = 1.98\, kg/min^3$$

$$D\,[liter] = \left(\frac{9.00\ kg}{min}\right) * \left(\frac{m^3}{1.98\ kg}\right) * \left(\frac{1000\ liter}{m^3}\right) * \left(\frac{min}{4200\ rev}\right) * \left(\frac{2\ rev}{cycle}\right) * \left(\frac{1}{0.91}\right)$$

$$Displacement = 2.4\ liters$$

With this modest level (for a diesel) of turbocharging a displacement almost identical to that of the spark-ignition engine can be achieved. Several options may be available to further optimize this engine; recognizing as well the greater torque rise capability of the diesel the resulting package will be quite attractive.

Heavy Truck Engine The diesel engine used in a heavy truck application will be optimized very differently. The desired rated power in this engine will be 300 kW. The combination of high load requirements and very long life expectations in a much heavier engine dictate a lower rated speed—1800 rpm is very typical. The high torque rise requirements will result in the need for greater excess air at rated power, so an air-to-fuel ratio of 32 to one is chosen. In order to provide the required air flow, the turbocharger will be set up to provide 3 atm. of boost pressure. A large charge air cooler will still allow a charge temperature of 47 °C (probably necessary in order to meet exhaust emission requirements). Finally, the combination of lower speed and higher boost will result in lower specific fuel consumption. 210 gm/kW-hr will be assumed. The resulting displacement is calculated as:

$$\dot{m}_{air} = (300\ kW) * \left(\frac{210 gm}{kW\text{-}hr}\right) * \left(\frac{kg}{1000 gm}\right) * \left(\frac{hr}{60\ min}\right) * (32) = 33.6\, kg/min$$

$$\rho_{port} = (3.0\ atm) * \left(\frac{1.01 \times 10^5\ N}{m^2 atm}\right) * \left(\frac{K}{287\ N\text{-}m}\right) * \left(\frac{1}{320\ K}\right) = 3.3\, kg/min^3$$

$$D[liter] = \left(\frac{33.6\ kg}{min}\right) * \left(\frac{m^3}{3.3\ kg}\right) * \left(\frac{1000\ liter}{m^3}\right) * \left(\frac{min}{1800\ rev}\right) * \left(\frac{2\ rev}{cycle}\right) * \left(\frac{1}{0.91}\right)$$

$$Displacement = 12.4\ liters$$

This again is very typical of the conditions and engine displacements seen in heavy trucks and construction equipment.

It must be noted that recent advances in turbocharger controls, while beyond the scope of this book, allow compressor outlet pressure to be more closely controlled versus engine speed. As a result, it may not be necessary to provide as much excess air at rated power as used in these examples. Repeating the calculations with rated power air to fuel ratios on the order of 20 to one allow specific power output to be substantially increased. Examples are seen in many of the recently introduced high-performance diesel engines.

5.3 Engine Up-rating and Critical Dimensions

Perhaps one of the most common challenges faced by engineers working with internal combustion engines is that of increasing the output of a production engine. The engine was developed at a displacement determined by the rationale described in the preceding section. Now that the engine is in production market demands indicate the need to increase the power output by perhaps 15 or 20 %.

From the discussion just presented several options for increasing the engine's power output can be readily identified. Small increases might be achievable through fine-tuning—perhaps improving the volumetric efficiency or reducing specific fuel consumption. However while a few percent power increase might be achieved the results are seldom sufficient to fully provide the required additional power.

Another approach that might be taken with spark-ignition engines is that of increasing the engine speed. The leverage this provides is significant, but invariably it results in fuel economy penalties due to increased friction and pumping work. In many cases it cannot be considered at all due to increased inertia forces and stress in the reciprocating components.

The next option might be to add a supercharger or turbocharger. For a spark-ignition engine either option might be considered although they both add cost. The engine must be significantly modified to ensure that the combustion process does not violate knock limits, and that durability is not sacrificed. In the case of modern diesel engines a turbocharger has already been fitted, so the turbocharger would be resized for increased intake manifold pressure. This too requires re-optimizing the combustion system such that peak cylinder pressure limits are not exceeded, but it is often the most attractive approach for diesel engine up-rating.

Especially in the spark-ignition engine, increasing the displacement is often the only viable approach. On older engine designs this was often easily done, as engine dimensions were quite generous. This is no longer the case since considerable attention is now paid to minimizing weight and package dimensions. The challenges of increasing the bore or stroke of an engine are detailed in Chap. 8 where the critical dimensions and resulting design trade-offs are identified.