Chapter 9
Propulsion for Flight: Power or Thrust?

The modern jet engine is a bit mysterious. Does it work like the engines in our cars? How and why is it better than the piston engines of the time during and after World War II? The obvious answer has to do with the ability of modern airplanes using jet engines to fly faster, higher, and farther. The reasons are interesting from historical and technical viewpoints and our focus will center on the latter. That will involve extending the ideas developed for understanding the function of the wing. To wit, the energy conservation law developed for the behavior of the flow along a streamline will have to be used in a more general form to include manipulation of the air when we compress it or allow it to expand to do something useful. After all, we want the engine to be practical and get work out of it. The heretofore assumption of adiabatic flow, i.e., flow without heat input, will have also to be revisited for the combustor because we are going to add fuel to air and burn it!

As the wing produced momentum as downwash that we exploited for lift, the propulsion system's function is to produce momentum of its own. The reason is identical: a force results from changes of momentum and we will want to do a lot of that in order to be able to propel an airplane forward at high speed.

So, what is a propulsion system? It is nothing more than the means to take in air and expel it at higher speed in the form of a jet. In that sense, it is a machine that pumps air. The propeller-driven airplane carries out that function by rotating wing-like elements with power input from an engine that produces mechanical power. The air used for propulsion does not participate in the production of the power. By stark contrast, the jet engine intimately intertwines the two functions of power production and propulsion. The jet engine does it in mysterious ways that involve the laws of heat physics raised earlier in connection with flow along a streamline. The pros call that thermodynamics, but don't let that term be scary!

For brevity, I will refer to the Internal Combustion Engine or equivalently, the Otto cycle piston/cylinder gasoline engine, as an ICE. For simplicity, the discussion of the jet engine functionality will focus on the basic turbojet. Thus, the terms 'jet engine' and gas turbine engine are, for our propulsion purposes, equivalent. Extension to consideration of turbofans and other gas turbine engine types will be made further on.

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First let's tackle the two engines and see how they are different and how they are similar. Both are *heat engines* that produce power from the heat obtained by burning fuels. The power is ultimately manifest in the propulsion jet produced. In both cases, the goal is to produce the thrust necessary to overcome drag. A distinction between the two engines is that the power output from the ICE is *shaft* power whereas the power in the jet engine resides in the gas jet produced. The distinction between interest in power and thrust may be ascribed to a historical evolution of book-keeping associated with the reality that developing the piston engines was logically treated as separate from developing propellers. For the jet engine, the power produced is less interesting than the thrust, hence a lesser interest on power per se. That is not to say that it is unimportant because it is the centerpiece of any discussion of *how well* the jet engine works to produce thrust. This dimension was tackled in connection with the discussion of propulsion efficiency.

9.1 The Engines: Stark Differences

The piston engine (ICE) processes air in piston/cylinders where the air processed is taken in batches through a series of *time separated* events. By contrast, the gas turbine engine carries out similar, though not identical, events in a *spatially separated* set of components that operate separately, steadily, and continuously. That is the first important difference between these two engines. The second is, as stated above, that the air processed by the ICE is generally not part of the propulsive jet whereas the air processed by the gas turbine is the jet, all of it.

The ICE engine therefore operates independently of the flight speed of the airplane in which it is installed. It must, however, deal with the static atmospheric environment of the airplane, namely the density of the air at the altitude where the airplane is flying. Consequently, the ICE performance depends primarily on altitude. At higher altitude the atmosphere is thinner (less dense) than at sea level. At these higher altitudes, the finite volume of the engine's cylinders takes in a correspondingly reduced amount of air mass with each intake stroke of the piston/cylinder. The necessary reduction of fuel to burn with the diminished amount of air reduces power and that, in a nutshell, is the Achilles heel of the piston engine. The ICE's development was nevertheless essential for practical flight because, for the first time, an engine light enough and powerful enough could do the job. Much effort has been spent on mitigating the altitude limitation with superchargers and turbochargers that have been effective, but never to the extent one might wish.

The turbojet engine is quite different. All the air used for propulsion is processed by the engine. That fact places a premium on efficient air handling in every component of the engine. The net distinction between the two propulsion systems is that the ICE/propeller jet's large diameter and modest ability to add momentum to the air contrasts starkly with the jet engine's jet high velocity and rather small volume flow rate (cubic feet or cubic meters per second).

What kind of thinking went into the idea of a turbojet? The history reveals similar thoughts by engineers in Germany and Great Britain during the 1930s and 40s. Names associated with this engine development include the principal contributors Frank Whittle in Great Britain and Hans von Ohain and Anselm Franz in Germany. Others, of course, helped lay the foundation for what these men brought to reality. This history is well told elsewhere and our focus here is on the technical underpinnings related to the function of this engine.

9.2 Limits of the Old

To begin, we explore the workings of the piston engine. The ICE produced mechanical power by compressing air in a piston-cylinder, burning fuel in the compressed space, and realizing a rapid and great increase in pressure. The piston then allowed expansion with a much larger force on the piston and therefore larger power output from the piston; importantly, more power than it took to compress the air. The process of compression and expansion in the confines of a piston and cylinder (hence the word *internal*) was, at the time, the best way of handling the gases involved. In the ICE, combustion takes place in a very short time while the piston hardly moves. This combustion process is termed to be at *constant volume*[1] and the goal is to raise the gas pressure.

The efficient compression process by means of piston within a cylinder took time to develop. As rings, seals, valves, etc., were successfully improved, they were quickly adapted to propelling automobiles and, in short order, aircraft. The ICE rapidly supplanted and displaced the only other way to produce mechanical power, namely the steam engine, an *external* combustion engine because the heat is supplied to the pressurized water from the outside. Its virtue was the ability and ease to compress (or perhaps better, pressurize) liquid water. This process was and is easy to do with a pump and allows the generation of high-pressure steam to act on a piston. The pressurization of the water did not require large amounts of compression power. That was pivotal in the steam engine becoming the first practical way of generating mechanical power from heat.

The ICE does not offer many options for improving performance. The performance measures are usually the power output, the fuel consumption rate, and the engine weight involved. The compression is limited by the volatility of the fuel in the fuel–air mixture being compressed lest it ignite before the piston reaches the so-called top dead center and result in potentially damaging pre-ignition. The main challenge for this engine type is to maximize the amount of air processed efficiently to realize a large power output. This feature is central in determining power output. Another challenging aspect of the design is the valving to manage flow in and out of the cylinder without overheating the valves themselves. After all, the exhaust gas

[1] The piston moves a little during the combustion, however, this descriptive notion is a good approximation of reality.

from the ICE is hotter than practical materials can easily handle in a continuous exposure. A number of valve configurations were tried and used, chief among is the common poppet valve and the less common sleeve valve pioneered by Bristol in Great Britain. The flushing of the cylinder space by fresh, cool air after combustion mediates internal surface temperatures and effective cooling of the external structure of the cylinder are key features of any design that allows it to be successful.

The practical option available for increased power is increased volume (the displacement) swept by the piston(s). That makes the engines larger and heavier. Nevertheless, progress in increasing power output per unit engine weight improved steadily over the years that these engines were the power source for all airplanes in aviation's youth. The zenith of their time is characterized by their production of one horsepower per pound of engine weight or one horsepower per cubic inch of piston displacement. One of the important means of achieving such performance levels was supercharging that primarily helped overcome the limitations imposed by the low density of air at high altitudes. In supercharged engines, the power necessary to drive it was obtained from tapping into the power from the crankshaft for a net gain in power from the engine as a whole. There was another way of getting such performance improvements and these were directly linked to ideas about the jet engine.

The ICE produces a high-pressure gas exhaust because the very high-pressure, very hot gas can only be expanded so much by a piston designed to compress the incoming air with the same piston stroke. The noise and hot, high-pressure gas emanating from these engines are evident manifestations that there is a lot of energy in the exhaust that might be used productively. Indeed, attempts at increasing engine power by taking advantage of the situation were developed: notably turbocharging (with or without intercooling), and the related turbo-compounding where exhaust turbine power is added to the power output shaft by appropriate gears.

Figure 9.1 illustrates several aspects of a supercharged piston engine for aircraft. The valves are the site where a limit on air processing capability is imposed on any piston ICE engine by limiting its rotational speed. This limit is a consequence of the relatively small flow area that can be made available by an open valve and the flow choking[2] in the presented passage. In the image, the green duct carries the incoming air to a poppet valve at right. The exhaust valve is at left. The lower picture is of the same display showing the radial flow supercharger (compressor) impeller with its green outlet duct funneling air to the intake valve. The impeller operates at many times the crankshaft rotational speed, hence the necessary gearing to drive it. At right are two of the rearmost set of pistons with the air cooling fins, cylinders, and crankshaft connections. The cam races for actuating the valves are shown but hard to discern. This Pratt & Whitney R-4360 engine is built with four sets of seven cylinders, 28 in all, and produced about 4000 hp. Parenthetically we note that the cooling air takes about 10% of the fuel's heating value away as a total loss that cannot be utilized for power production.

[2] See comments on choking of flow through nozzles in Chap. 13.

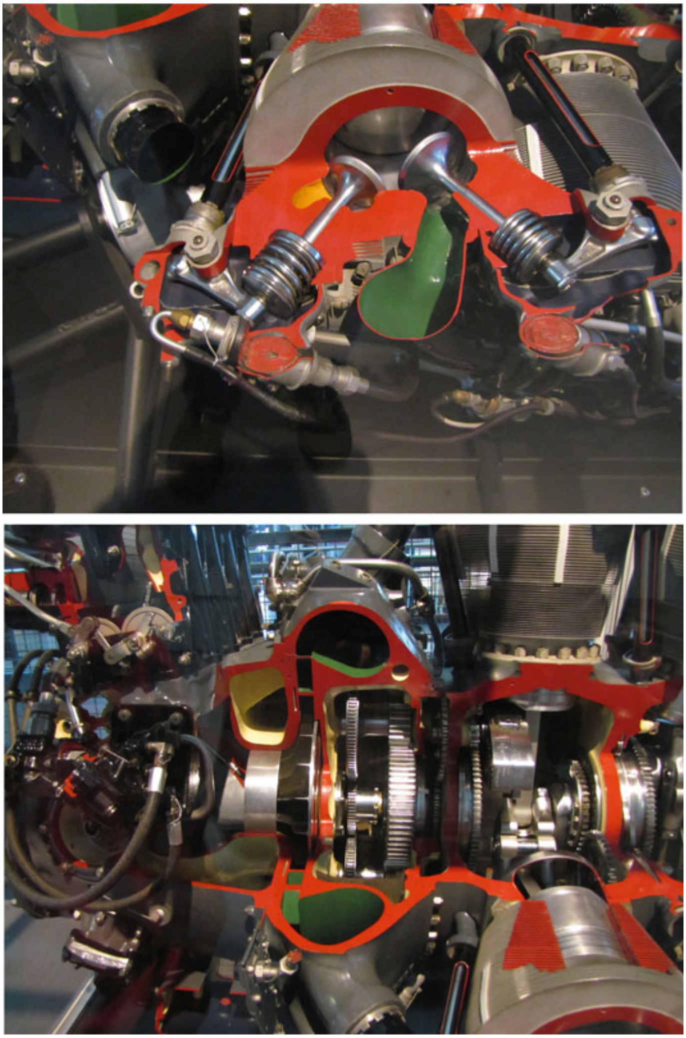

Fig. 9.1 The complexity of the piston aircraft engine and a dream world for mechanical engineers; here sectioned views of a P&W R-4360 (Pictures from an exhibit at the Udvar-Hazy Center of the Smithsonian National Air and Space Museum)

Naturally, there were improvements made throughout the history of its development, but the fundamental limitations were inherent in the engine. Breakthrough improvements were not to come. There was a new engine on the horizon.

9.2.1 The First Jet?

Before leaving the ICE, it is interesting to note that building and flying a "jet" airplane with an ICE as a power source for a compressor was considered by the innovative Italian airplane-building count Gianni Caproni. He built an airplane (the Caproni Campini N.1) using a piston engine driving a compressor that led air to an afterburner and a nozzle. He believed this airplane to have been the first jet powered airplane. It flew on August 27, 1940, exactly one year *after* Hans von Ohain's airplane, the first gas turbine powered jet airplane that flew on August 27, 1939. That flight was kept a secret by the German government and the Heinkel company that built it.

So, why use a new jet engine? The answer is simple: we want to fly faster! While Caproni's attempt to do away with the propeller was noble, it failed. It was, however, the right thing to try because it is the propeller that imposes a speed limit on the airplane. The flight speed of a propeller powered airplane cannot come close to approaching the speed of sound. The power supplied by an ICE are simply inadequate for an approach like that of Caproni. This reality underlies people thinking about "jet" engines to fly faster.

The road to the jet engines in use today is mile-stoned by a succession of inventions, innovations, advances in the understanding of the physics, and the reality of everyday operations. These innovations are well covered in the literature and we leap directly to the turbojet of the 1940s and its successor, the turbofan twenty years later. What is somewhat skipped over in this discussion is the early use of the radial flow compressor that allowed jet propelled flight to be realized but rather quickly faded into a historical footnote. This now uncommon compressor type did break the ice and pointed the way to a new engine type.

9.3 The Gas Turbine or 'Jet' Engine

Describing the jet engine is a bit like describing the human body. Where do you start? The heart, the brain, the skeletal structure, its function, or what? The jet engine is, mercifully, quite a bit simpler but not straightforward. It is also a *system* that has components that have to function together for the engine to perform well. Before we can talk about the components, we have to develop tools that allow a somewhat quantitative discussion of what happens to the air as it streams through a gas turbine engine.

When one contrasts the ICE and the gas turbine as engines, it is apparent that the ICE relies on constant volume combustion carried out in a few thousandths of a second, with compression, combustion and expansion carried out in the same space. The alternative way for burning fuel to generate heat and, with it, run an engine, is to employ steady combustion from a continuous source of heat. Thus, separate components are called for. The idea behind the gas turbine engine is to process large amounts of air so that large amounts of fuel can be burned for the realization of large amounts of power. The compressor to furnish this compressed air could have the absurd form of a piston-cylinder machine as used in industrial processes, but that would entail the air flow rate limitations inherent in the ICE and be unacceptably heavy. Could a compressor based on the idea of a rotating wheel accelerating air to higher speed and then slowing that air to realize high pressure be made to be useful? The answer is yes, because the dynamic pressure of flow is raised behind a propeller by virtue of the work input into the propeller. But how to do that effectively? How to raise the pressure by a much more substantial amount? And how to provide the necessary power?

One of the ideas that had to be part of the thinking about this new engine is that a turbine can produce many times the amount of power that an ICE can. The turbine is a steady flow machine with which there was a lot of industrial experience in hand. Perhaps a steady flow compressor and a turbine can be made to work together.

9.4 Is the Gas Turbine Engine Like Another Familiar Engine?

Suppose for a moment you are standing in front of a jet (or equivalently, a gas turbine) engine sectioned to expose its inner workings. The natural question "How does it work?" is often answered in terms of the similar processes in an automotive ICE. That may not be the best way of doing so, particularly because the heat addition part of the engine, as embodied in the combustion chamber, is nothing like the related process in an ICE.

The fundamental processes of compression, heating, expansion, and heat rejection must be present for all types of heat engines. It is the way that heat is added to the engine that differentiates the ICE and the gas turbine engine at a fundamental level. The work processes of compression and expansion, be they by piston or aerodynamic means, are a secondary but important *mechanical* distinction between these and other engines in common use.

The ICE is unique in that it operates with the fundamental processes listed above in a time-separated fashion in the same space. The gas turbine and the steam engine operate with these processes with separate components and are much better for comparison purposes. These two engine types operate with *steady* flow of their respective working fluids, air and water (as steam). To first order, a thermodynamic analysis of any engine does not care whether the processes are steady or sequential, just as long as they are present.

9.4.1 Yes, the Steam Engine!

Let us look at what goes on in a steam engine so we can relate events there to those in a jet engine. For our purposes, the steam engine model to have in mind is of a steam railroad locomotive that might commonly have plied the rails in the years between 1850 and 1950. It is very much a forebearer of the gas turbine engine even as the medium processed differs substantially from the air we might wish to use in a flight propulsion engine.

While most discussions of the thermodynamics of any heat engine invariably start with the compression part of the cycle, we will start with the biggest and most important part, the heat addition aspects. In the steam engine, the heat addition to the pressurized water is steady as the water 'flows' by the heat source. Here heating occurs in a large flow-through vessel, a boiler and a steam superheater. The boiler is fed by high pressure water and serves to create a very much larger volume of steam at the same high pressure. In the boiler, each cupful of water becomes about a hundred of such cupfuls of steam!

The resulting steam provides power by letting it expand against a piston within a cylinder connected to the wheels of the locomotive. That is how it generates mechanical power.[3] The power can also be extracted by expanding the steam through a turbine. The machinery for doing so has been employed for the production of electric power since the 1920s. The word "expanding" is used here because, in either work extraction process, be it in a piston/cylinder or through a turbine, the volume of the steam increases to allow work to be done the piston head or the turbine blades.

In order to make the argument that the work available by a greater volume of air plausible, consider the following thought experiment that leans on the use of pistons and cylinders. A piston within a cylinder made to undergo a certain amount of compression displacement, i.e., over a fixed stroke, requires work. Such a compression process can be very close to reversible because it can be designed so that the gas temperature is increased by compression does not lose any of the heat. In practice, good thermal insulation or a rapid movement will allow the process to be approximately adiabatic and reversible. If this piston is subsequently allowed to expand back to the starting point, then the work invested is recovered and, as far as the universe is concerned, nothing happened.

Now let us pretend that we have invented a piston and cylinder whose diameter can be made larger at will. This is improbable but not impossible. If the air in the compressed space is heated by some means (including combustion of fuel) in such manner to keep the pressure constant by letting our magic piston/cylinder grow as heat is added, we end up with a larger piston which is acted on by a larger force (because the piston area is larger) than the force required to compress the gas before heating. Allowing that piston to expand through the same stroke as executed in compression leads to a greater work output than was required by compression. The result is a net production of work for an input of heat. This is the way to think about an engine

[3] While the steam is admitted periodically into the cylinder, the process could be regarded as steady over a longer observation period.

with constant pressure heat addition, … if one insists on dealing with pistons and cylinders. At the end of the expansion process, the air is hotter than it was before compression and the heat associated with that is waste heat, a necessary consequence of the production of work from heat by any engine. This argument is, of course, an invocation of somewhat realistic magic, so let us return to real engines.

Before going on to the gas turbine, we note that the pump required by the steam engine is small in its role because water is incompressible so that raising its pressure does not require much in the way of power or machinery. That fact alone made the steam engine relatively easy (mechanically and in terms of the power required) to devise and allowed it to be the first heat engine of the industrial age. The supply of high-pressure air to the combustion chamber of a jet engine will not be nearly as easy.

In a gas turbine, heat is added to air by injection of a small amount of fuel into the compressed air stream. For all practical purposes, the combustion process that takes place within the engine just creates hot air. After all, air is mostly chemically inert nitrogen. The heat provided in a gas turbine combustion chamber typically increases the gas volume (per unit mass) by a factor of 2–3 times (depending on design conditions) the volume of air entering the combustion chamber. This much lower volume expansion sets the gas turbine engine apart from a steam engine. Further, in the gas turbine, there is no phase change from liquid water to steam. The *gas* turbine engine processes only gas (and tiny bit of liquid fuel).

Is the steam engine able to provide power for flight? Not likely. The steam engine requires lots of water and water is heavy as is the boiler. In a locomotive application, resupply of water emitted as spent steam is as important as ‘refueling.’ The locomotive carries tons of fuel and water in a tender right behind the locomotive. The weight considerations associated with the use of water preclude the steam engine for aviation. There are other issues. Water has properties that limit its performance in a steam engine. Most important of these is that the amount of heat necessary for making steam is very large. That has an important negative impact of the efficiency of the engine as a power provider. These realities did not deter potential aeronauts in the mid-nineteenth century from thinking about powering flight vehicles with the steam engine. It was the only engine available then. Such dreams were, however, neither practical nor realized.

The attraction of the gas turbine is that it works with *air* that is readily available for a flight propulsion engine and does not have to be carried along. That suggests a great advantage that an engine using air could be light in weight. Indeed, it worked out that way.

In order to examine the jet engine in greater detail, we have to step back and look at the way we have to describe what happens as air proceeds through its components. Thus, a brief pause to re-examine the parameters and the principles we developed in connection with flow along streamlines.

9.5 Energy Conservation Again, for Steady Flow Through Engines

For wings and external flows, we considered situations where the geometry determines the condition changes along a streamline. The energy conservation statement can also be applied to *internal* flows where the flow is bounded by walls and perhaps manipulated by work or heat interactions. Instead of describing flow along a streamline, the words and ideas will change to apply to a *stream tube* which is really nothing more than a bunch of streamlines undergoing the same or similar changes. The walls will play roles similar that played by a wing surface in that flow area changes will be called for to slow or speed the flow. To generalize the First Law, we extend it to apply it to situations where mechanical power (or work per unit time) is added to or removed from a stream tube. This is what is done to flow through a compressor or a turbine. Another extension is required to include the possibility of adding or removing heat from the flow. That extension is necessary for the description of flow through combustors or heat exchangers. The properties that reflect such interactions are total enthalpy (or equivalently, total temperature) and, depending on how well it is done, the total pressure. These interactions will be central to the functioning of a jet engine.

9.5.1 A Little Mathematics, Briefly

For the technically oriented reader, the next few short paragraphs are meant to display what the First Law looks like (as an equation) for the more general (steady flow) situations and how it applies to components of a jet engine. Inclusion of the mechanical power and heat terms transforms the First Law to reflect total temperature increases in direct measure of work addition and/or heat addition to a component. The inlet flow condition is described as state 1 and outlet as state 2. The engineer would write this for a unit of mass as:

$$C_p \cdot T_{t2} = C_p \cdot T_{t1} + w + q$$

where $C_p \cdot T_t$ is the total enthalpy (per unit mass, C_p is the specific heat), w is the work, and q is the heat input. Normally, both work and heat inputs would not be involved in the same component. The work term (w) would apply to compressors and turbines while heating (q) applies to combustors (or heat exchangers).

Depending on how efficient the work processes are carried out in the relevant work components, the total pressure change may be as good as dictated by an isentropic process. No real component is ever that good, but the technology is reasonably close to achieving such levels of performance. Thus, the total pressure increases in a compressor a bit less than ideally and decreases in a turbine, a bit more than ideally.

In a combustor or heat exchanger, the transfer of heat generally leads to a reduction in total pressure and good design aims to minimize it because the work components have to make up for such losses. For descriptive purposes, it is generally acceptable to talk about heat addition in combustors as taking place at constant pressure.

So much for the technical underpinnings.

9.5.2 *What Happens in a Real Jet Engine?*

In order to set the stage for the thinking about the new engine type, we look at some numbers related to the first jet engine in service, the German Jumo 004 flown in the Messerschmitt 262 jet fighter during WW II. The rather modest compressor (pressure ratio 3.1) required about 4000 hp from the turbine component for the engine as a whole to provide 2000 lbs of thrust. The turbine power output was substantial; it was certainly greater than what a typical piston aircraft engine could deliver. Thus, the turbine becomes an important component of the engine. With such thinking, the basic configuration of the gas turbine engine took shape.

The idea was that the compressor would pressurize the gas to a pressure *higher* than required for the jet so that the turbine can power the compressor and there would sufficient pressure left over to produce a jet.

The sketch in Fig. 9.2 illustrates the variation of the important (total) pressures and temperatures through a gas turbine engine. These values would be measured by a probe that brings the flow to rest locally. As a result of mechanical power addition, these flow parameters increase in the compressor (C) and decrease in the turbine (T). In the combustion chamber, or burner (B), the gas temperature rises and the pressure stays close to the value at entry. This interesting dimension of the combustion process is examined in greater detail in Chap. 12.

The temperatures and pressures reached in the engine are critical indications of engine performance. The pilot of a jet engine powered airplane is informed of engine performance through the instrumentation in the cockpit. The relative (total) pressure relation (turbine outlet to compressor inlet, see figure) is displayed as Engine Pressure Ratio (EPR), necessarily greater than 1.0 when the engine is operating. This ratio is the most important indication of engine performance as a thrust producer.

The mechanical integrity of the engine's hot section is ideally made by measurement of the turbine inlet temperature. Because of the high temperature at this point in the engine and the probe location, the measurement is difficult to make reliably in the long run. A measurement at the turbine exit (or in mid-turbine) is easier. It can and does serve as an indication of the temperatures in the hot section of the engine. The

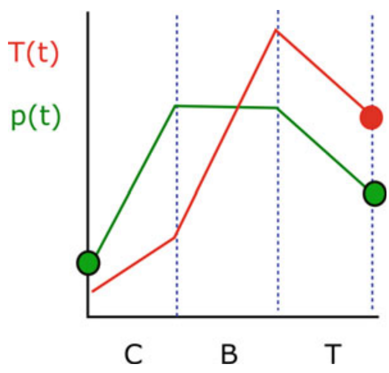

Fig. 9.2 Simplified schematic variation of total pressure and total temperature in the principal components of a gas turbine or turbojet engine. The dots are the quantities involved in the cockpit display of engine performance

gauge display for the pilot is usually labelled as Exhaust Gas Temperature (EGT) or Turbine Exit (or Outlet) Temperature (TET or TOT).

9.6 Design Issues

This idea of an engine arrangement was the focus of the pioneers in the late 1930s. It required a number of difficulties to be overcome at the same time. The basic ideas about what is necessary were available, but could they be combined into a practical engine that can outperform the ICE? The first issue that had to be tackled included devising a way compressing lots of air, efficiently. As it turned out, that proved to be the most challenging of the issues facing a successful engine design.

A second issue was adding heat to the compressed air by mixing it with fuel and burning it. At the time, industrial practice involved combustor chamber volumes that would be unacceptably large for an airplane engine. The combustor volume would have to be reduced.

A third issue was, and still is, that the temperatures reached by burning hydrocarbon fuel with air could be very high, higher than what metallic materials can stand for prolonged exposure. Here the challenge is the maintenance of structural integrity of the turbine by virtue of the temperature and exposure to the combustion gas involved. The metal surfaces will have to tolerate the hot combustion gas and last for acceptably long lifetimes. The turbine was, nevertheless, seen as practical because the technology resembled that used in the steam turbines operating at that time. Their aerodynamic performance was pretty well understood but the nature of combustion gas as the medium was a new challenge.

So, the stage was set. The industrial world had experience in a number of related areas that might be exploited for the process of building this new engine. Specifically, experience with turbocharging of aircraft ICEs was in hand. In these devices, ICE exhaust is made to drive a charging compressor to allow the engine to operate with greater air mass than with normally aspirated engines. In fact, the air path through a new 'jet' engine resembles that through a turbocharged ICE with the difference that the heat source *is* the ICE. In short, the turbo-compressor feeds air into something that heats it and the resulting hot combustion exhaust gas is expanded in a turbine to drive the charger. The turbine exhaust is normally not used for jet thrust. The power in that stream is too low to be useful.

In our telling of the story of the evolution of the jet engine, we will take the viewpoint of emphasizing the engineering ideas and connect them to some of the people involved. The people involved, Frank Whittle in Britain and the engineers in Germany, were on opposite sides of a competition and later a war, so that information sharing between them was very unlikely. Their respective governments classified work related to the development as state secrets. Nevertheless, engineers were guided by the physical realities and tended to think along parallel lines. Consequently, we can develop the thinking about the gas turbine engine while jumping back and forth across the war divide and thereby see how the necessary understanding grew into practical engines on both sides of that chasm. While this discussion may feel like a departure from one concerned with vortices, the loop will be closed with ideas about the jet engine that have important operational similarities shared with the behavior of wings.

In the next chapter, we examine the compressor. It was *the* most important component of the engine because the compression process is difficult.