SECTION 1 - INTRODUCTION

1.1 THE BASIC CYCLE

The Gas Turbine, like any other heat engine, is a device for converting part of a fuels chemical energy into useful available mechanical power. It does this in a manner similar in many ways to the cycle used by a 4 stroke Internal Combustion engine. The main apparent difference is that work is accomplished in a continuous manner in the turbine power process, whilst in the reciprocating engine, this is an intermittent process. Figure 1 below illustrates the similarities between the two.

The combustion process raises the air temperature to a flame zone value of between 2,500 and 3,200°F. This is immediately reduced to usable values by the mixing of secondary air that enters the combustion chamber through specifically placed holes.

The hot, high pressure gas mixture is then ducted to the turbine section where it is allowed to expand down to exhaust temperature. In the expansion process, enough energy is removed from the gas to drive the compressor, the unit driven auxiliaries such as the accessory gear box, fuel pump, cooling water pumps, lube oil pumps, etc. and the load, which may be an alternator with a gear box, a compressor, or a pump etc.

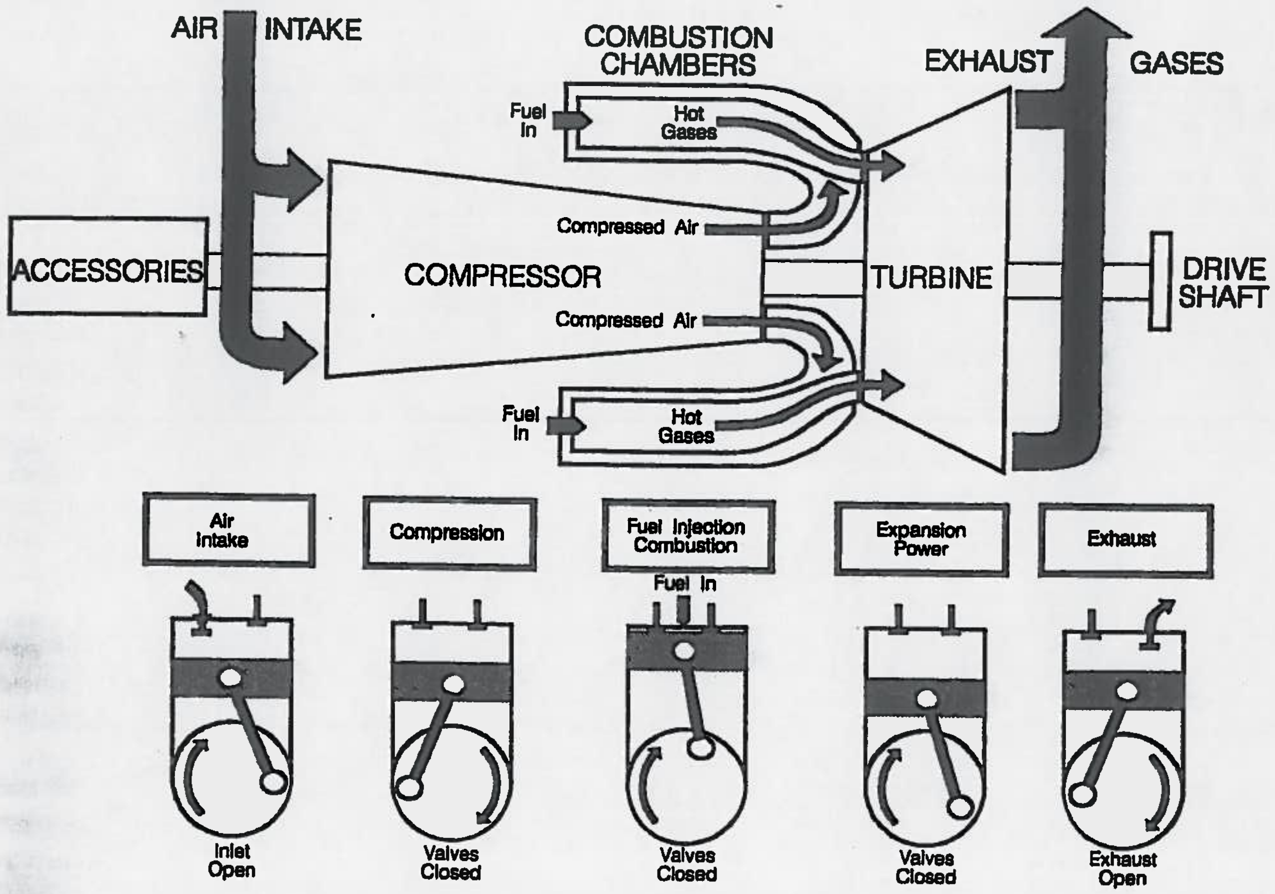

Fig. 1 Similarities in Gas Turbine and 4 Stroke Cycle.

As indicated by this illustration, air is drawn into the compressor, through an air filter situated in the "filter house". This filter removes any harmful solid particles from the air stream, before it enters the compressor. After filtration the air is compressed, in multiple sets of fixed and rotating blading, as it passes through the axial compressor. As well as being raised to a higher pressure, through the compressor stage, the air also becomes hotter. This hot, compressed air is then fed to the Combustion System where it mixes with injected fuel. Here the fuel burns and adds its energy to the air.

The used gas is then allowed to flow to the exhaust stack system. Since there is still much heat energy in this gas, it can be put to use in a variety of ways, such as air or water heating process drying or as hot air feed supply to a separately fired boiler, waste heat recovery boiler. Any of these heat recovery methods helps to increase the overall thermal efficiency of the turbine cycle.

The Compressor

Several types of compressors are available for Gas Turbine applications. They are Centrifugal, Axial Flow and the Intermeshing Lobe Types. All have been used by different manufacturers, depending on the needs of their Gas Turbines.

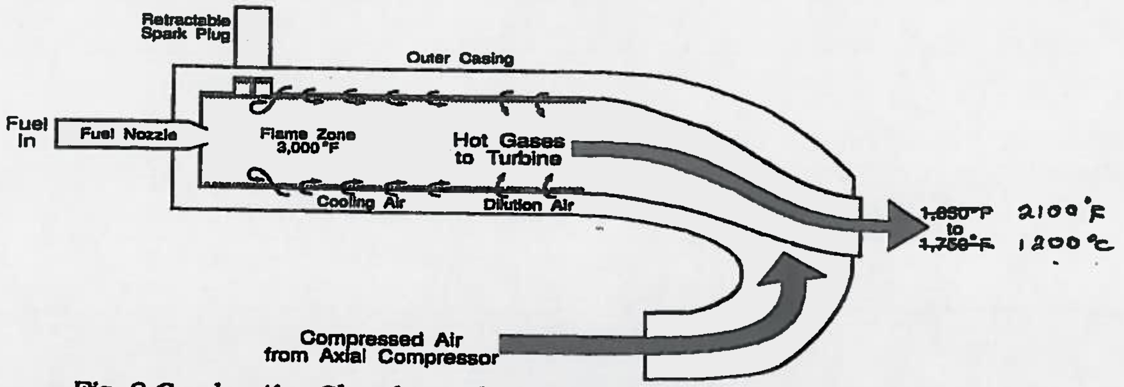

Fig. 2 Combustion Chamber - Flame Zone & Air/Gas Paths.

The G.E./J.B.E. Company uses the Axial flow type for all of its main compressors and this was chosen primarily for its ability to pump large volumes of air at better efficiency levels, than either the centrifugal or lobe types. Axial flow compressors are so designed that the air moves axially through the blading with essentially no radial travel. This type of compressor is made up of rows of air-foiled shaped blades with each set of rotating blades followed by a set of similar stationary blades. G.E./J.B.E. commercial compressors are designed to divide the pressure rise about equally between rotor and stator.

The Combustion System

The combustion zone of a turbine is the space required for the actual burning of the fuel and the subsequent dilution by secondary air from flame temperatures of 3,000°F, down to usable values of between 1,650 and 1,750°F. For G.E./J.B.E. units, this normally takes place within a group of combustion chambers, which are located inside the machine package (F.S.5). The combustion chamber comprises an outer casing, an inner casing (or "liner") and the necessary air and gas passages (see fig.2).

Simplified Outline of Combustion System

As shown in figure 2, combustion takes place at the flame zone, inside the inner casing of the combustion chamber. The outer wall of the inner casing is cooled by streams of air which are made to flow through louvres punched in the inner casing wall material. This air stream flows close to the wall and thus keeps the material cool, and so reduces thermal stress.

The Turbine Section

It is within the turbine section of a gas turbine that part of the thermal energy contained in the hot gas, provided by the combustion system, is converted into mechanical energy. Sufficient mechanical energy must be taken out of the gas stream to supply the power necessary to drive the axial-flow Main Compressor, the Driven Auxiliaries (such as lube oil and fuel pumps), provide for bearing frictional losses and have enough excess power to do a

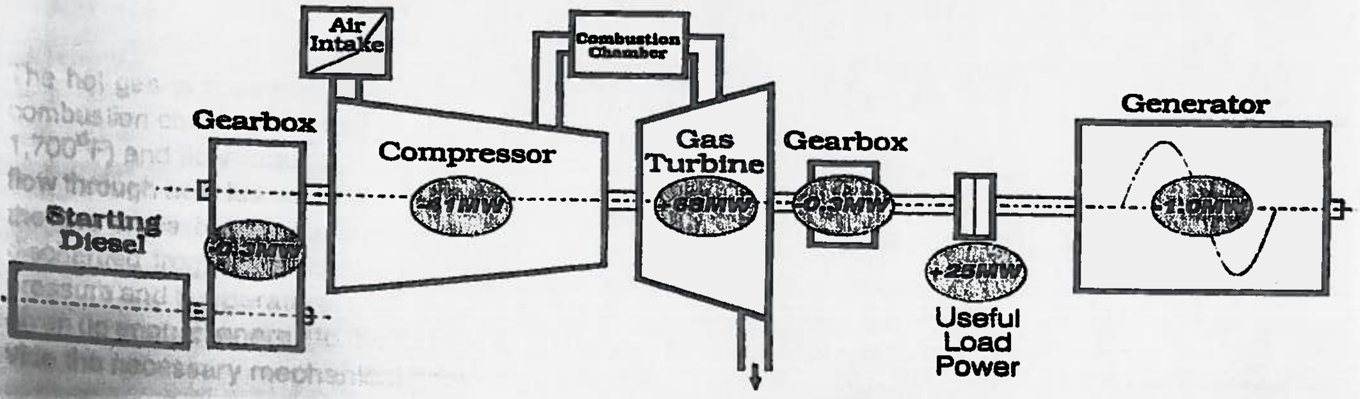

Fig. 3 G.T. Arrangement showing Energy Values.

reasonable amount of external work, such as drive a generator, load compressor, or some other type of load equipment (See figure 3 for typical values).

Two main types of turbine blade designs are used for energy conversion. They are called **Reaction** and **Impulse** designs. In the Reaction type, the hot gas is allowed to expand in both the rotating and stationary blading. This is an efficient method of extracting work from a gas stream, but since not much pressure drop can be used per stage, many stages are required. In the Impulse type, which is used by G.E./J.B.E. most of the pressure drop occurs in the stationary elements with only a small percentage taking place in the rotating parts. **This type has the advantage of being able to do more work per stage (hence fewer stages) than the Reaction type.** It also permits larger pressure and temperature drops to occur in the stationary parts, rather than in the more highly stressed and difficult to cool rotating elements.

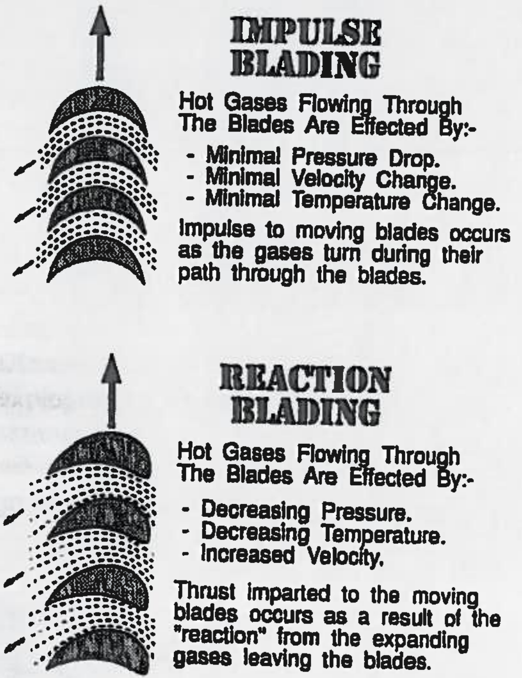

Fig. 4 Impulse & Reaction Blading Designs.

The hot gas is delivered to the turbine, from the combustion chambers, at a temperature (1,000 to 1,700°F) and flow required by the load. During its flow through nozzles and buckets (turbine blades) the gas loses both heat and pressure until it is discharged from the final stage at exhaust stack pressure and temperature. In the meantime, it has given up enough energy to the turbine rotor to provide the necessary mechanical power.

So far, discussions and descriptions of the turbine cycle have primarily been for a single shaft non regenerative unit. Whilst this type of machine is simple, powerful and reasonably good on thermal efficiency, some applications require more flexibility of operation and thermal efficiencies, than this basic machine configuration is capable of providing.

For this reason the two shaft machine was developed. This type has the load turbine and the compressor turbine on separate shafts, with a controllable angle nozzle in between. The "angle" nozzle is effectively a variable area orifice. Some of the advantages of this type of construction are.-

- (a) Better part load thermal efficiency.
- (b) Ability to run compressor and load shafts at different speeds so that the best results can be achieved.
- (c) Lower starting power required.

With wide open nozzles the ΔP over the high pressure turbine is maximised. Thus the turbine develops more power in starting which reduces starting power required.

Higher overall thermal efficiencies may be achieved by the addition of a regenerator. In this component, turbine exhaust gas is allowed to give up some of its heat to compressor discharge air.

In this way, heat that would otherwise be wasted is returned to the cycle, thereby reducing fuel required and increasing the power output.

The Accessory Section

This section of the machine includes:-

- The Starting Device. (diesel engine, expansion gas turbine, or electric motor)
- Lube Oil Tank. (containing the requisite amount of lube oil - 1,700 gallons for F.S.5)
- Auxiliary Gearbox. (which drives fuel pump, gear lube oil pump, gear hydraulic oil pump, atomising air compressor and water pump)
- Hydraulic Ratchet. (for cooldown purposes)
- Electro Mechanical Stop Valves.
- Lube Oil and Fuel Oil Filters.
- Pressure Gauges and Switches
- Emergency and Cooldown Electrically Driven Lube Oil Pumps.

The auxiliary gearbox is initially driven by the starting device, but in normal operation the gas turbine itself supplies the motivating power.

1.2 THERMO-DYNAMICS

Many Thermo-dynamic cycles are possible with a Gas Turbine, but basically that used by G.E./J.B.E. is based on the Brayton, or Joule cycle.

The Otto Cycle (See fig.5).

This consists of a compression phase, then spark ignition and an explosion phase, that raises the pressure very high, then an expansion phase, where the power is delivered and then finally an exhaust phase.

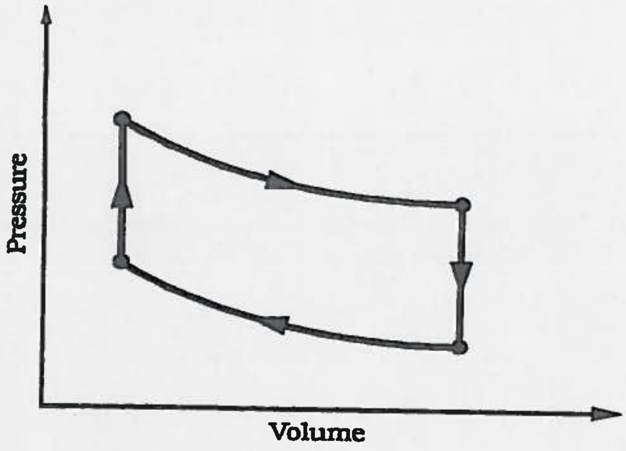

Fig. 5 The Otto Cycle.

This is the ideal cycle under which the I.C. engine operates with spark ignition. By changing to:-

The Diesel Cycle. (See fig.6)

The explosion is eliminated and instead of having a constant volume combustion, we inject fuel at a rate which will hold the pressure constant, even though the piston is moving back.

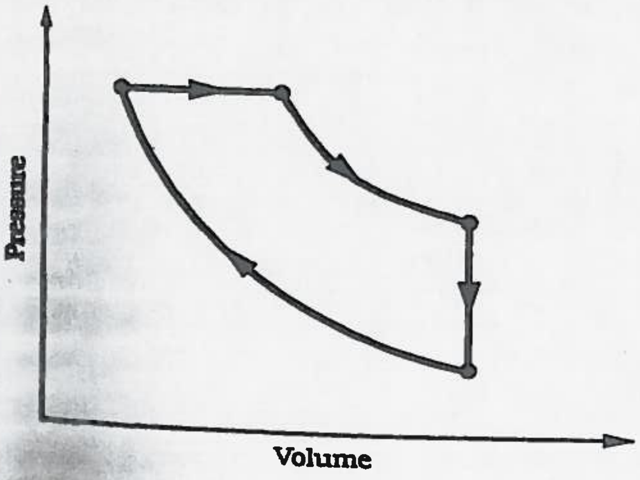

Fig. 6 The Diesel Cycle.

On this diesel cycle, the exhaust stroke must be the same length as the compression stroke, because a reciprocating engine is built in this way. At the end of the expansion stroke, the exhaust valve must be opened to let the mixture exhaust to atmosphere

The Brayton or Joule Cycle. (See fig.7)

In this cycle we have a longer exhaust stroke than a compression stroke. In this manner, the gas can be expanded all the way down to atmospheric pressure, before the next stroke is started.

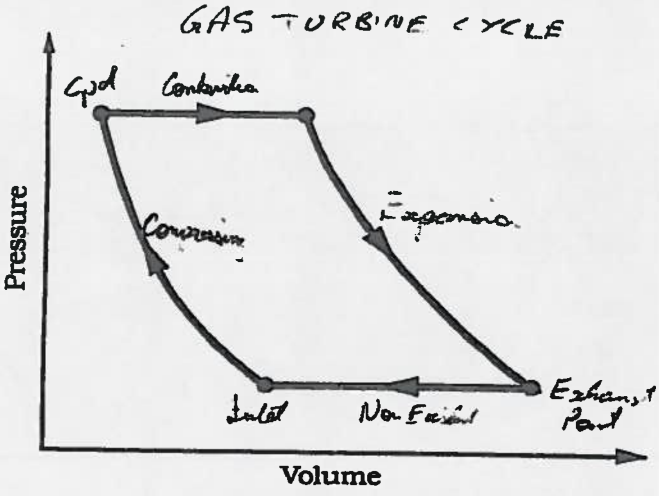

Fig. 7 The Brayton (Joule) Cycle.

For convenience, this cycle can be thought of as a "Batch" process. By batch we mean that a particular chunk of fluid is used all the way through the cycle.

NOTE! These are ideal cycles that require a reversible adiabatic compression and expansion:-

- Reversible means there is no work lost to friction. (i e. none of the work done in compressing this gas is used to overcome Friction.)
- Adiabatic is a constant heat cycle. (i.e. there is no heat lost to the casing, etc.)

The Brayton Cycle has also been worked out for a steady flow process, and this steady flow process becomes the simple gas turbine cycle. There is no diagram of pistons and cylinders available that accurately represents the required result. Instead, it is necessary to think in terms of separate components represented by boxes and triangles -- see figure 8.

CHAPTER FOUR

FLUID FLOW IN GAS TURBINE ENGINES

INTRODUCTION

The successful operation of a gas turbine engine depends upon fluid flow and resulting energy transformations. The overall energy concepts were presented in Chapter Three. Fluid mechanics is a difficult subject and the theory will not be presented here. The purpose of this chapter is to describe some processes that occur during energy transfer between the gas stream and the blading of turbomachinery. Subjects to be discussed are flow separation, compressor stall and surge, fluid friction, turbulence, and choke flow. These are the most common fluid flow phenomena encountered during gas turbine engine operation.

SEPARATION AND STALL

Each stage of an axial compressor is essentially a row of airfoils, which can be compared to airplane wings. Several concepts can be explained using this comparison. Figure 4.1 illustrates the effect of the angle of attack of air flow around an airfoil.

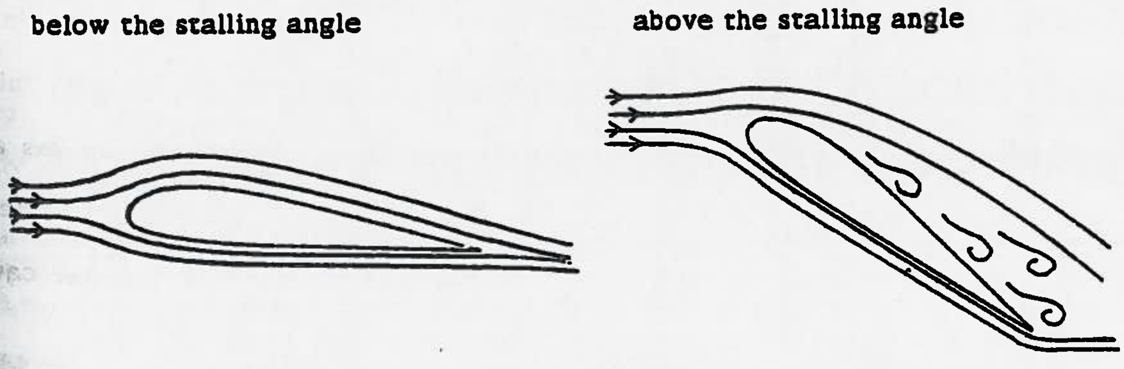

Figure 4.1 - Typical air flow around an airfoil with the angle of attack below and above the stalling angle.

If the angle of attack is below a critical angle, the flow is smooth. Above this "stalling angle" the flow breaks away from the upper surface and separation occurs. Separation is characterized by slowing of the fluid at the surface to zero velocity followed by flow in the opposite direction resulting in the formation of eddies that are shed off the trailing edges. The angle of attack is determined not only by the position of the blades themselves, but also by the speed of rotation and air mass flow. Some engines employ variable stators to correct for changes in operating conditions.

Separation severely limits the performance and efficiency of the compressor which is said to stall when separation occurs. The effect of compressor stall depends on the operating conditions and generally manifests itself as either surge or rotating stall.

SURGE AND ROTATING STALL

In a gas turbine, the compressor is the component that forces the flow through the rest of the machine. In effect, the compressor "sees" the burner and turbine as a flow restriction. If the flow restriction is too great, excess pressure will result. If this pressure is higher than the compressor can physically sustain, the air flow falls off drastically and delivery pressure drops. These conditions cause the compressor to stall and the pressurized combustion air (and sometimes the burning fuel) will reverse and flow back through the temporarily disabled compressor. The sudden release of pressure produces a loud "bang."

When the pressure in the combustion system is sufficiently relieved, the compressor can recover. The pressure again rises in the combustion system and the cycle repeats at a rate of several times per second in a typical engine. This repetitive stalling and recovering of the compressor is called surge. Because the pressure changes and flow reversals are so violent, there is little question when surge occurs. The principal risk from surge cycles is mechanical damage to the engine. If surge occurs, the cause must be removed immediately, or the engine must be shut down.

Rotating stall is a phenomenon that occurs under normally stable operating conditions if, for some reason, the air flow is not uniformly distributed among the flow passages. For example, if there is a problem with the flow to passage II in Figure 4.2, some of the air will be deflected to each of the neighboring passages (I and III). The angle of attack is increased for passage III and decreased for passage I. Passage III then stalls while the flow to passage II recovers. During stall of passage III, flow is deflected to IV and II so that IV stalls. In this way, the stall rotates from passage to passage around the rotor and thus the term "rotating" stall.

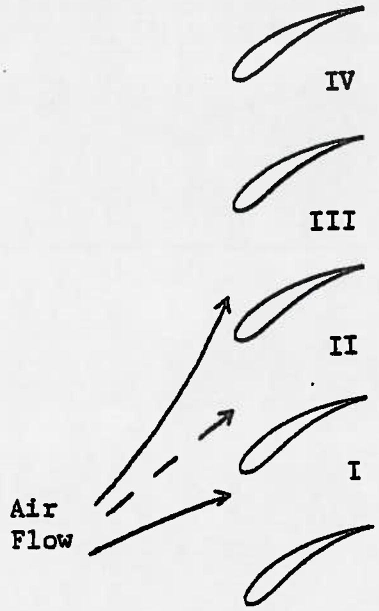

Figure 4.2 - Compressor rotor blades illustrating air flow involved in rotating stall.

There may be little external evidence that the compressor is in rotating stall. The principal observation is that the supply of additional fuel will not accelerate (or will slow) the engine. This situation carries the risk of overtemperature damage to the hot section of the engine or fatigue failures due to resulting vibration. Again, some action must be taken to remove the cause of the rotating stall, or the engine must be shut down.

Recovery from rotating stall is an interesting problem. Removal of the original cause of the compressor stall may not produce recovery. In this case, additional action to further reduce pressure demand on the compressor must be taken. For example, gas turbine compressors sometimes utilize bleed valves that are opened to prevent rotating stall from occurring (or to permit recovery) as the compressor speed increases during starting of the engine.

The causes of compressor problems leading to surge or rotating stall in gas turbine engines are many. It might be assumed that the engine design would prevent operation leading to these conditions, but this is not always possible. Many engines will have a region of rotating stall during starting. Since the starter is assisting the engine during this period, this can sometimes be tolerated until the compressor speed increases sufficiently to meet the pressure demand.

For a stationary engine, surge should not occur unless an off-design operating condition is encountered. This could be plugging of the turbine by deposition, too-rapid acceleration demand, or compressor fouling. In aircraft engines, distortion of the inlet flow pattern can produce rotating stall and/or surge. This sometimes occurs in taxi and take-off with high crosswinds or in military aircraft with violent maneuvers.

FRICTION AND TURBULENCE

In the discussion of individual compressor and turbine efficiencies (Chapter Three), reference was made to friction and turbulence as causes of inefficiency. These are two of the major causes of energy waste in gas turbine engines.

The amount of energy transmitted to or from moving blades is largely determined by the shape of the blade. The compressor and turbine blades are designed so that maximum transfer can be achieved. It is important that the gas flow follows the blade passages closely. This can be accomplished by narrow spacing between the blades. However, if the blades are too close, giving too narrow a flow passage, fluid friction effects will play a dominant role with resultant energy waste. This is an example of the way in which friction can significantly affect efficiency. Friction is a phenomenon that is present anywhere that a fluid is flowing, and in varying degrees of severity.

Turbulence is a complex phenomenon that is generally defined with mathematics beyond the scope of this course. It is sufficient to say that in the main air stream it is a non-steady flow with random fluctuations in both speed and direction. Turbulence effects can range from insignificant to quite costly in terms of the energy wasted, and are closely associated with flow separation. Turbulence results in substantial "mixing" of the air which is necessary in the combustion zone for efficient burning and must be tolerated to a certain degree. However, in the compressor and associated ducting, turbulence can result in significant pressure (energy) drops. The gas turbine designer must minimize turbulence related losses.

CHOKE FLOW

Gas velocities in the gas turbine engine are quite high. As mentioned in Chapter Two, velocities through the combustor can be on the order of 100 - 200 ft/sec. The velocities are even higher through the compressor and turbine stages as energy transformations cause increases in kinetic energy. The limiting velocity is the local speed of sound (Mach 1). Choking occurs at this point. Practically speaking, this represents the maximum mass flow that the compressor or turbine can deliver at a particular speed. The operating point for a compressor is generally at a flow below choke so that there is flexibility of operation. On the other hand, the turbine is usually operating at (or close to) choke flow. This subject will be further discussed in Chapter Five.

CONCLUSION

In the compressor, the rotor imparts energy to the air and directs it into the stator passages. There the fluid decelerates and kinetic energy is transformed into pressure. In the reverse situation, the pressurized combustion air is directed into the turbine rotor passages by the stator (nozzles) and pressure is converted back to kinetic energy and ultimately shaft power (and possibly thrust). These energy transformations are achieved through manipulation of a fluid and are based on fundamentals of fluid dynamics. It is assumed that the student will be concerned with an adequately designed engine.

Symptoms of off-design operation which is damaging to the engine include fluid flow problems such as surge and rotating stall. Fluid friction and turbulence can also rob useful energy and decrease efficiency. If the problem is not obvious (such as surging), a decrease in output or an increase in fuel consumption with no increase in output can be symptomatic of problems. The most common flow problem is due to deposits on, or erosion of, blades in the compressor or turbine. However, deterioration of flow passages at any stage can be a cause of decreased overall efficiency.

NOTES