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THE FEASIBILITY OF USING AN AIR TURBINE TO DRIVE AN AFTERBURNER FUEL PUMP

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ABSTRACT

Current fighter engine designs extract power to drive the afterburner fuel pump through the use of a gearbox. The presence of the gearbox only allows the fuel pump to operate at a fixed proportion of engine speed. In addition the fuel pump is continually rotating, although not pumping fuel, even when the afterburner is not engaged. This article investigates the feasibility of using an air turbine to drive the afterburner fuel pump in preparation for supporting an all-electric engine.

Utilising performance data for a typical modern military engine, 1-dimensional design techniques were used to design several radial turbines to power the afterburner fuel pump. A choice of an axial or a radial air turbine is possible. Both were reviewed and it was determined that a radial turbine is optimum based on manufacturability and (theoretical) efficiency.

Several design iterations were completed to determine the estimated weight and size based on various air off-take locations, mass flows, and rotational speeds. These iterations showed that increasing mass flow allows for lower rotational speeds and/or smaller diameter rotors, but with a corresponding increases in thrust penalties

NOMENCLATURE

1	Turbine Inlet
2	Turbine Exit
C	Absolute Velocity, Compressor
cm	Centimeter
hb	Hub
HP	High Pressure
IP	Intermediate Pressure
LP	Low Pressure
m	Meter
mn	Meanline
r	Radial Direction
RPM	Revolution Per Minute
sh	Shroud
U	Blade Speed
W	Relative Velocity Vector
x	Axial Direction

1.0 INTRODUCTION

Jet fighters employ the use of afterburning to augment the available thrust to the aircraft by as much as 50%. This is used for take-off, climb, acceleration, and engagement [(1)].

Afterburning is only used for limited periods during a mission because of the high fuel consumption. The fuel is supplied to the afterburner through a separate fuel system and fuel pump.

Current configurations for military fighter aircraft use a gearbox to drive the afterburner fuel pump. The gearbox is a proven technology, but to support an ‘all electric’ engine’ concept it is necessary to look at other ways to drive the afterburner fuel pump. Other methods can include an electrically driven fuel pump or an air turbine driven pump.

The all electric engine assumes that a generator is used to supply power to all currently mechanically driven accessories, including the afterburner pump. If the full benefits of the concept are to be realised the accessory gearbox should be eliminated.

However, despite the advantages of replacing present forms of secondary power with electrical power, the high power consumption of the afterburner pump coupled with the fact that is used for such a small proportion of the flight, means that an electric drive system for this pump may not be the optimum solution. In the case of a military aircraft there is not such a strong case to replace the extraction of bleed air, and since the AEE does not assume necessarily the elimination of bleed air, there is much scope in investigating the feasibility of an air turbine driven afterburner pump.

The electrically driven pump has an advantage in that an electric generator is also needed to power other aircraft systems. Accordingly, a simple increase to the generator output with the addition of the electric motor attached to the fuel pump is all that is needed to provide this sort of means to power the fuel pump.

The penalty of an electrical motor driven pump is the weight of the components in the electrical system. The weight of the system is detrimental to not only the components themselves, but also to the secondary weight of the rest of the aircraft through additional structural support and fuel. It is recognised that for every extra kilogram of weight on the engine, an extra 6 to 10 kg of secondary weight will be added to the aircraft [(2)]. For a twin-engine fighter, that translates to 12 to 20 kg of extra weight.

A second disadvantage is the problem of how to drive the generator to get the power needed. On an 'all electric engine' the power will most probably be available from integrated starter/generators in the core of the engine. However, on a 'more electric engine' this will still require a gearbox or some other type of turbine extracting air from the engine to drive the generator.

Against this background, an air turbine to drive the afterburner fuel pump on a typical modern military engine was investigated. The use of an air turbine is an old concept, but not widely employed. Concorde, for example, has been flying around for over 20 years utilising an axial air turbine to drive the afterburner fuel pump.

The advantage is that only during times of need is the air turbine in operation, meaning that there is only a drain on the engine when the afterburner is selected. This can be looked at in two ways. Firstly that during times of non-afterburner usage there is not the constant power drain on the engine. The second is that when the afterburner is used the power drain on the engine should be minimised. However, this small amount of power drainis considerably less than the power gained through the use of afterburning.

It should be noted, however, that if the conventional accessory gearbox is to be retained, an air turbine does not seem to be needed.

1.2 POWER REQUIREMENTS.

With the assistance of TRW, the power consumption of a typical afterburner fuel pump was determined. Clearly, this varies with the amount of fuel flow required and the pump impeller diameter. For the fuel system to operate properly, a 70 bar pressure rise across the pump is required. To produce this pressure rise it was estimated that a well designed pump requires a maximum input power of 100 kW at 30000 RPM and 110 kW at 40000 RPM.

The input power required is also affected by the velocity of the aircraft and the altitude at which it flies. This is shown on Figure 1.1. However, the values listed above were the primary values used to determine the initial input requirements for the air turbine as they represent the flight conditions where the fuel flow is the highest.

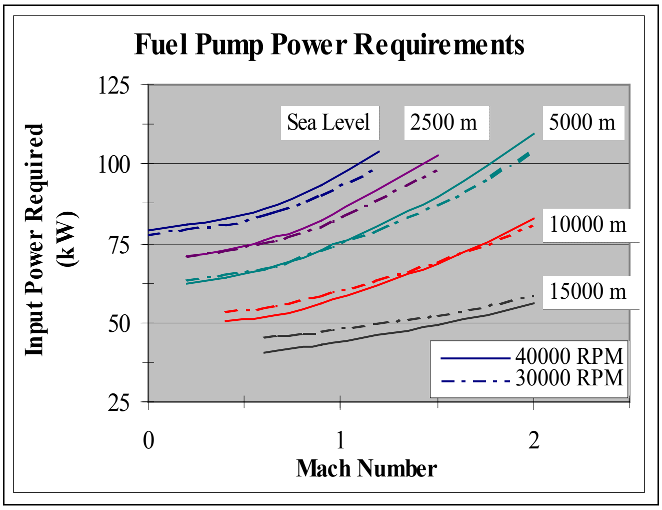

FIGURE 1.1: AFTERBURNER FUEL PUMP POWER REQUIREMENTS AT VARIOUS FLIGHT VELOCITIES AND ALTITUDES.

As expected, this Figure shows an increase in required power as the flight Mach number increases. It also shows that at higher altitudes a lower input power is required for a given Mach number. Naturally, at lower altitudes the maximum flight speed is lower, thus the calculations only go up to attainable flight velocities.

The input power required is based on the rotational speed, fuel pump impeller diameter, and fuel flow. The fuel flow is dictated by the engine performance and was determined by Laskaridis [(3)] using a Cranfield University computer code known as Turbomatch. The latter facilitates design and off-design engine performance assessment.

1.3 ENGINE MODEL.

The configuration of a typical modern military engine entails an LP spool and an HP spool. The engine was modelled using bleed downstream of an LP compressor with a pressure ratio of 4.2 at sea level. The HP spool consists of a compressor with 2 possible bleed air off-take locations. The first is assumed to occur at the point in the HP compressor where the pressure ratio is 8.4. The second is located after the HP compressor before the combustor where the pressure ratio is 26.

The other possible locations for bleed off-takes are after the HP and LP turbine. However, the temperature of the flow after the HP turbine is too hot to be used to drive the air turbine. Performance model estimates provided by Laskaridis showed the temperature of the core flow is about 1300 K downstream of the HP turbine [(3)]. This is clearly much too hot to use in an un-cooled metallic turbine.

It will become evident that reducing the amount of bleed flow from the engine is paramount. Furthermore, air turbines designed using bleed air from the HP turbine was not pursued as these would require the use of additional air from another location just for cooling. However using bleed air off the LP turbine was possible and initial designs were examined.

1.4 OBJECTIVE.

The objective was to consider the feasibility of driving the fuel pump for the afterburner of a typical modern military engine using an air turbine. The above parameters dictated that the air turbine could operate at 30000 RPM as long as it produces the 100 kW of power or at 40000 RPM, when producing 110 kW of power.

In addition, once the type of air turbine was determined (i.e. radial or axial) it was decided to constrain the design to fit within a cylindrical envelope of 15.0 cm diameter by 35.0 cm long. The reasons for choosing such a small envelope are two-fold. The first is to limit space within the fuselage, while the second is to maintain a low weight.

2.0 AIR TURBINE TYPE.

Several types of air turbine are suitable for driving the fuel pump. These include the radial in-flow, the radial out-flow and the axial turbine. A radial in-flow turbine was chosen because of the following advantages over the axial turbine. (See Walsh and Fletcher [4])

- Capable of much higher expansion ratios (up to 8:1),
- Lower manufacturing cost for the same amount of expansion,
- Ideal for wheel diameters less than 35.0 cm.
- Better isentropic efficiency for capacities < 0.05 $kg{\cdot}K^{0.5}{\cdot}s^{-1}{\cdot}kPa^{-1}$, because as the size of the of the axial turbine is reduced there are increasing tip clearance losses.
-

However, with these advantages of course come disadvantages. These include an increased susceptibility to foreign particle damage [7], higher thermal stresses and a larger frontal area.

The radial in-flow turbine is the logical choice over the radial out-flow turbine. Looking at a velocity triangle for a radial in-flow turbine (Figure 2.1) the rotational velocity of the turbine itself will contribute positively to the total work contribution.

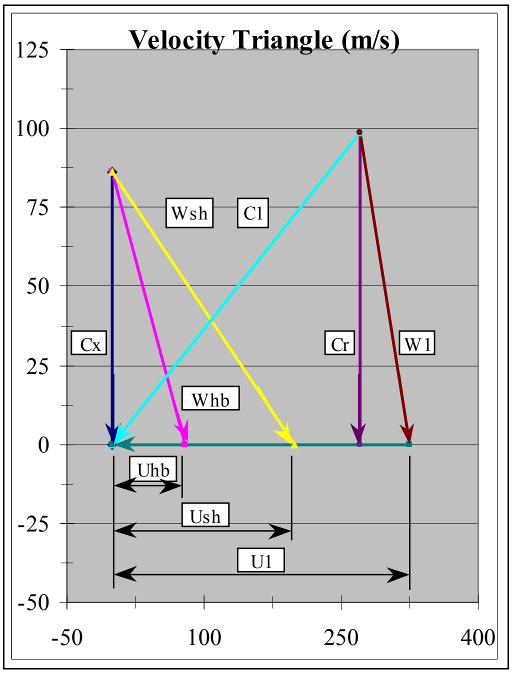

Figure 2.1: Radial In-Flow Turbine Velocity Triangle .

In a radial out flow diagram, the inlet blade speed (U1) becomes smaller than the exit blade speed at meanline (Umn). In addition, the design of the rotor blades in the radial direction is more complicated for radial out-flow machines due to the combination of centrifugal bending stresses in non-radii aligned blades and thermal stresses [6].

To cope with the stresses, the blades are designed to be thicker at the rotor exit. This, however, increases the weight [6]. As the goal is to have a light and small turbine, a more detailed analysis of a radial in-inflow turbine was undertaken.

3.0 RADIAL IN-FLOW TURBINE DESIGN.

Several designs were examined for the rotor using a method outlined by Wilson and Karanititis [7]. The design of the volute geometry at the throat was undertaken using a method originated by Whitfield and Noor [8]. A dump type diffuser was also chosen. A spreadsheet with graphing functions was set up to automatically plot the cross-sectional geometry at the throat. The output is shown in Figure 3.1.

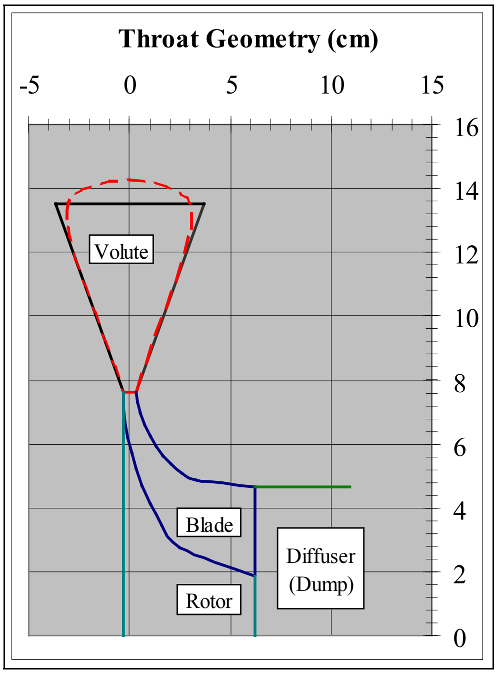

FIGURE 3.1: RADIAL IN-FLOW TURBINE GEOMETRY

Ideally, the relative flow velocity through the respective geometries dictates the blade and volute geometry beyond the throat. The 1-d designs created for this paper assumed a constant decreasing area for the blade and volute geometry. This was enough to get an estimate for the weight and maximum size of the turbine.

3.1 ROTOR DESIGN.

The rotor design was determined first since it is the primary factor in dictating the power out of the turbine. The variable parameters and recommended values relating to the design of the rotor are shown in Table 3.1.

Of course, the mass flow into the rotor was also variable, however, properties such as temperature and pressure were dictated by the values obtained from the engine model [3].

TABLE 3.1: CHECKS TO ENSURE A REASONABLE 1-D DESIGN.

Item	Recommended	Optimum
Inlet Flow Angle to the Rotor, $\alpha_{C,1}$ [7]	-	70°
Specific Speed, Ns [7]	-	~0.65
Blade Width to Inlet Diameter Ratio, B_1/D_1 [7]	-	~0.836
Hub to Shroud Diameter Ratio, Λ [7]	0.25 – 0.40	-
Shroud to Inlet Diameter Ratio, D_{sh}/D_1 [7]	< 0.9	-
Axial to Radial Flow Velocity Ratio, $C_{x,2}/C_{r,1}$ [7]	0.8 – 0.9	-
Hub to Rotor Relative Flow Velocity Ratio, $W_{hb,2}/W_1$ [7]	>1.1	-
Exit Mach Number [4]	~0.3	-
Rotor Axial Length Parameter, LP [4]	1.0 – 1.3	-

Although all these parameters can be varied, the primary ones are specific speed and mass flow. For example, by adjusting the inlet flow angle, there is a slight change in the required rotational speed of the turbine and a small reduction in diameter. Only the primary parameters, therefore, were adjusted to determine the size of the rotor.

It became evident while examining various alternative designs that blade tip speed dictated the output power of the turbine. This was in-turn dictated by mass flow into the rotor. This can be seen by looking at Figure 3.2, which shows that as the mass flow is increased into the rotor the blade tip speed is reduced for a given amount of outlet power.

Physically, this is important because the necessary blade tip speed is only obtained through the rotational speed of the rotor and the inlet diameter. It also became clear that the dual requirements of a rotational speed of 30000 RPM (or 40000 RPM) and a target diameter of 15 cm would not permit a solution for a radial turbine.

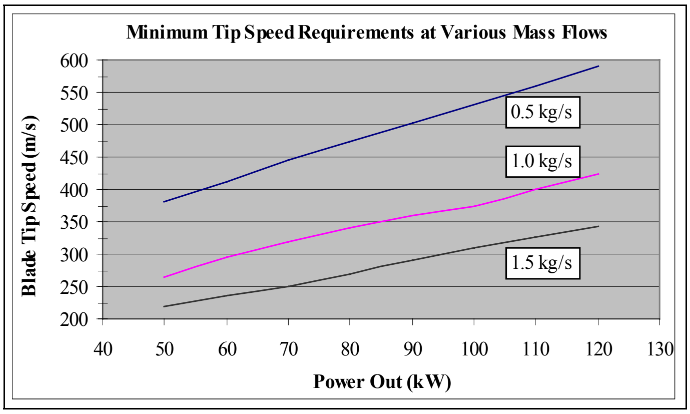

FIGURE 3.2: EFFECT OF MASS FLOW ON BLADE TIP SPEED AND POWER [9].

For a given mass flow, adjusting the specific speed allowed control of the rotational speed. By maintaining the desired rotational speed of 30000 RPM or 40000 RPM, the diameter was allowed to float until the required tip speed was met for the required power. Through this adjustment the specific speed was often well below the optimum value of 0.65. Figure 3.3 shows the physical effects on the rotor of adjusting the specific speed.

Naturally, the lower the specific speed the smaller the inlet blade width. Below a specific speed of about 0.15, Balje (1981) [9] excess efficiency penalties preclude the use of a radial turbine.

The meanline blade profile geometry was obtained using Lamé ovals [6]. This allows more degrees of freedom in satisfying end conditions [6] and also allows the development of continuous curves without discontinuities along the mean line radius [6].

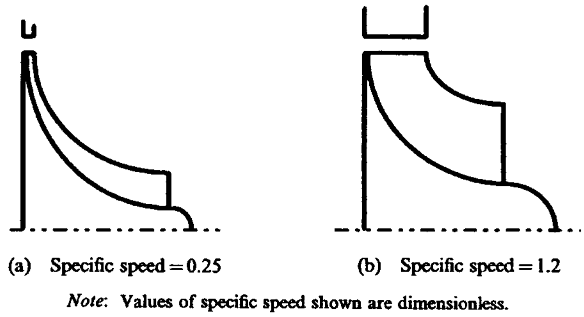

FIGURE 3.3: PHYSICAL EFFECT SPECIFIC SPEED ON ROTOR GEOMETRY [4].

3.2 VOLUTE DESIGN.

Flow is introduced into the turbine via a volute (see Figures 3.1 and 3.4). The volute creates a radial pressure gradient to change the flow of the air from its tangential entry to a relative radial direction for entry into the rotor [6]. Its design can affect the efficiency of the turbine. Ideally, it should create a constant change in Mach number through the volute.

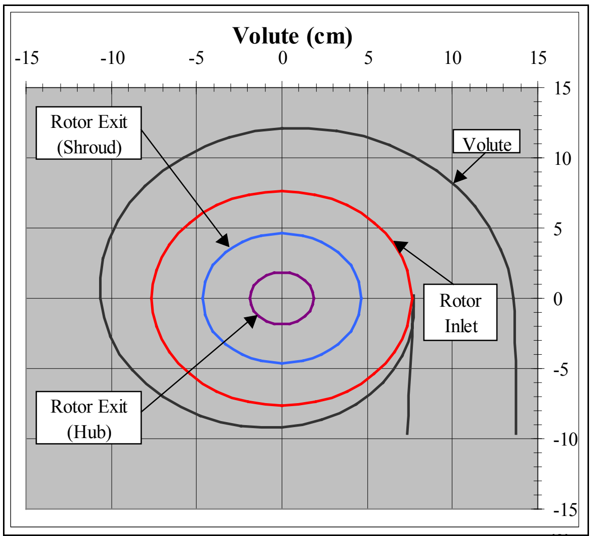

Figure 3.4: Turbine Cross-Sectional Area [9].

As mentioned previously, assuming a constant reduction in area was acceptable to determine the design of the volute after the throat.

Figure 3.1 shows the cross-sectional area of the volute at the throat. The solid line represents the calculated volute cross-section, while the dotted line represents what the actual volute cross-section would look like. The trapezoidal shape was chosen as a compromise in efficiency and size from Figure 3.5. The circular volute has a higher efficiency, while the triangular volute will result in a smaller overall diameter.

The last factor to discuss is the type of volute (i.e. vaned, vaneless, or variable area). A vaneless volute was chosen because they are smaller in size and cheaper to manufacture [11]. The vaneless housing also has a wider operating range at a given performance level [6]. Finally, the lack of vanes also helps to reduce potential excitation of the rotor since there will not be any aerodynamic disturbances in the flow.

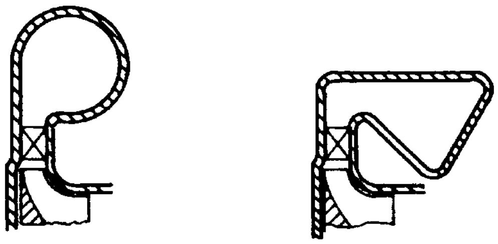

FIGURE 3.5: CIRCULAR AND TRIANGULAR VOLUTE CROSS-SECTIONAL AREA [10].

The main disadvantage to a vaneless housing is that the performance level or efficiency is often lower than a vaned volute [6].

Although maximum efficiency is always a goal, this air turbine will be operating off-design more frequently than at design point. Accordingly, a flat efficiency curve will be beneficial at off-design.

The inlet velocity, the inlet flow angle, the exit velocity and the exit flow angle in combination dictate the volute dimensions. The exit dimensions, velocity, and flow angle are fixed by the conditions the rotor requires at entrance. Inlet flow angles to the rotor of about 70° are typical, while Mach numbers vary. For a given exit Mach number the inlet Mach number can have a significant impact on the efficiency and the weight of the machine (see Figure 3.6). Realizing that, as the Mach number increases the efficiency is reduced because the passage losses increase in the volute.

Figure 3.6 shows the effect of inlet Mach number at 65° and 85° inlet flow angle. Both the effect on the outer diameter and the weight of the volute are shown. The Figure shows that as the inlet Mach number increases the outer diameter reduces. It will continue to reduce, but at the expense of increasing the width of the volute geometry. This is why the weight reaches a minimum and then begins to increase. The designs selected utilised an inlet Mach number corresponding to minimum weight.

Although desirable, a full analysis of the true flow through the volute was not undertaken.

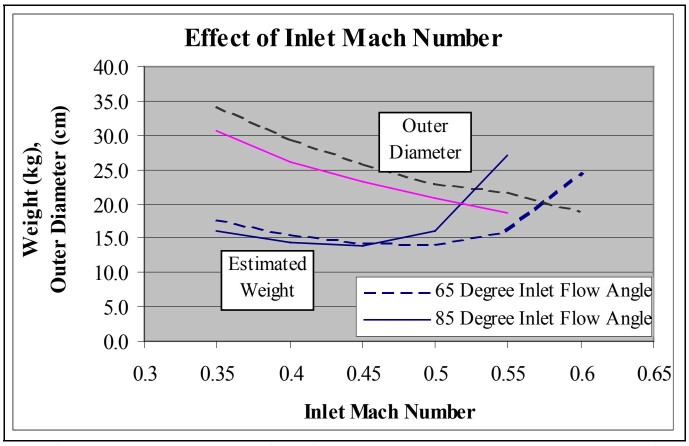

FIGURE 3.6: EFFECT OF INLET MACH NUMBER ON VOLUTE GEOMETRY [9].

3.3 DIFFUSER DESIGN.

Although the goal is to return the mass flow to the engine after the LP turbine, it proved to be impossible to diffuse it back to the pressure of the local core flow in the engine. The reason was the low axial exit Mach number at exit from the turbine, (typically less than 0.2). Accordingly, a dump diffuser was chosen for all designs.

It was assumed when estimating the turbine weight that the dump diffuser was the same diameter as the rotor at the shroud, while the length was half the inlet diameter.

3.4 DESIGN RESULTS.

Finally, the mass flow, bleed location from the engine, and rotational speed (30000 RPM and 40000 RPM) were varied to determine the effect on turbine outer diameter and turbine weight. The results can be seen in Figures 3.7 and 3.8.

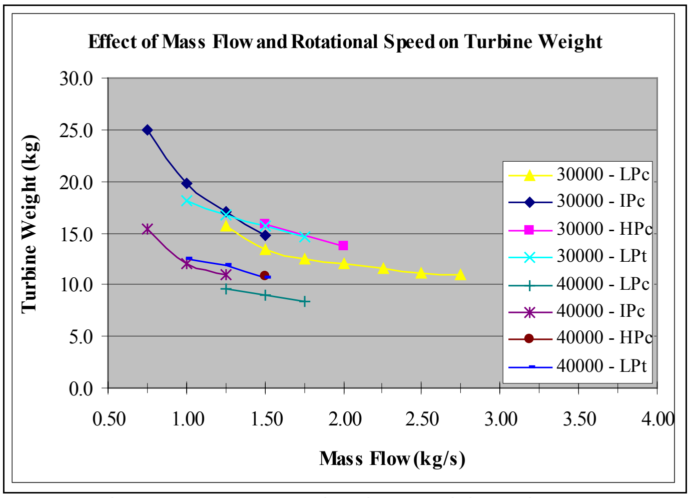

FIGURE 3.7: EFFECT OF MASS FLOW AND ROTATIONAL SPEED ON TURBINE WEIGHT [9].

While undertaking the design iterations it was noticed that with very low selected specific speed values the blade width at inlet became very small. In some cases only 1 mm in width was achieved. For obvious reasons such small sizes were ignored.

In addition, the hub to shroud and shroud to inlet diameter ratio had to be adjusted to achieve exit Mach number between 0.15 and 0.2. Whilst this was well below the recommended exit value of 0.3 recommended by Walsh and Fletcher [(4)], these were the best obtainable.

The effects of increasing the rotational speed were beneficial. In general the designs were 'better behaved'. These were also typically lighter and smaller than their counterparts at lower speeds.

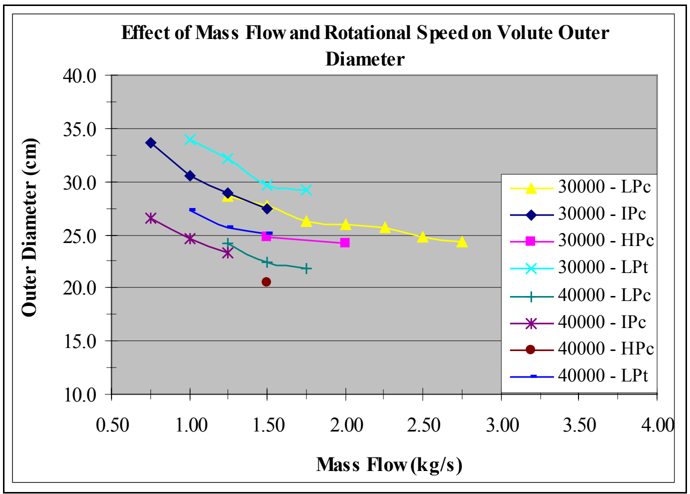

FIGURE 3.8: EFFECT OF MASS FLOW AND ROTATIONAL SPEED ON TURBINE OUTER DIAMETER [(9)].

Figure 3.7 is an estimate of weight based on various assumptions, such as a constant volute thickness, a solid rotor, constant thickness blades and manufactured from one material (specifically a nickel super-alloy).

Higher mass flows were not attempted for several reasons. Firstly, bleed of large quantities of air off the engine has a negative impact on thermal efficiency. Secondly, in some cases, the specific speed of the rotor was too high. Furthermore, the inlet area to the rotor became very large because the blade widths were increasing (although the diameter remained about the same). The increasing inlet area made it difficult to keep the exit area larger than the inlet area.

Inspection of the second Figure (3.7), it is noticed that the lowest weight may not necessarily correspond to the smallest overall diameter. This is because of other factors like the rotor length and the profile of the blade geometry.

4.0 DISCUSSION OF RESULTS.

Designs close to the target space envelope were developed through to 1-d off design. Only the HP compressor bleed version allowed the air to be returned to the engine downstream of the LP turbine. Basically, this was due to the low inlet Mach numbers. For a particular design, low inlet Mach numbers means lower exit Mach numbers. In order for the diffuser to be effective the Mach numbers realistically need to be sufficiently above Mach 0.2 to allow the diffuser to work effectively.

In order to increase the inlet radial Mach number the wheel tip speed needs to be increased through the use of smaller mass flows and principally higher rotational speeds (as opposed to larger diameters because of the weight penalties). This means a rethink of either the fuel pump or concepts without a gearbox.

With higher exit Mach numbers it will be possible to diffuse some of the kinetic energy to gain increased pressure for re-entry into the engine after the low-pressure turbine. This causes a smaller effect on the flow bled off the engine.

The trend in increasing mass flow reduces the overall weight and diameter of a rotor and its housing. However, increased rotational speed has a more significant effect. The difficulty is trying to hold a low rotational speed by increasing the rotor diameter, which results in long and thin rotor passages with very small blade widths.

The problem with the diffuser again is that the inlet axial velocity is very low, as a result of needing a reasonably low tip speed. Most turbochargers run at least twice the RPM of this turbine because of their lower mass flow. Although, it is desirable to operate at low mass, this cannot be achieved because of the need for a reasonably low tip speed.

Another disadvantage of large diameters is the effect on turbine weight. The average overall weight seemed to be around 15.0 kg, with some as high as 25.0 kg and others as low as 8.0 kg. The overall diameter was at an average around 25.0 cm. The effect of reducing outer diameter is often very similar to the effect of reducing estimated overall weight.

5.0 CONCLUSIONS.

The ambition to produce a radial turbine to drive an afterburner fuel pump in a space envelope of 15.0 cm diameter by 35.0 cm long was not achieved. This was due to the constraints imposed by limiting the permissible quantity of bleed flow and minimising rotational speed. It is, however, possible to produce a satisfactory solution if these constraints are relaxed.

The thrust penalties increase for an increasing amount of engine bleed flow. However, a specified low RPM requires a higher mass flow or larger diameter rotor and often a combination of both. The detriment to a larger diameter is the weight of the machine and the reduced efficiency. Simultaneously, the blade tip widths also reduce. The detriment to having a higher mass flow is the resulting low exit velocity. This precludes returning the air to the engine except when the air is bled from the high-pressure compressor.

The concept of driving an afterburner fuel pump with an air turbine is possible, but the need for the turbine to run faster makes it difficult to match with a fuel pump that requires 100 kW of power at only 30000 RPM.

Although the size targets have not been met, design iterations were carried out to determine the trends for the turbine design. It is possible to drive the afterburner fuel pump with an air turbine using bleed air off the engine, but not within the target space envelope. This comes with a penalty of high mass flow, or large diameter, or high rotational speed, or a combination of the three. Unlike a gearbox driven fuel pump where it is only running at a fixed proportion of the engine speed, the air turbine can be designed to operate at a specific rotational speed.

In addition, it has the benefit of only bleeding air (i.e. power) when the afterburner has been selected instead of constantly draining power. Since the usage schedule shows that the afterburner is selected for about 5% of the flight time per flight hour, that may hold another advantage beyond the scope of this article. This would allow the turbine to bleed a little more air to reduce the weight enough to provide positive benefits to overall fuel consumption and thrust for a given mission profile.

The estimated weight of the gearbox is about 35 kg (Laskaridis [3]) (although it is driving five other auxiliaries as well). This is higher than all of the designs reviewed in this study. Therefore, the bleed penalties may be acceptable due to a possible reduction in weight of the afterburner fuel system and overall aircraft weight. This was also concluded by Cumpsty [2].

With respect to reliability it can be said that all three designs, (i.e. accessory gearbox, air turbine and electric system), could offer acceptable standards of reliability with the final figure depending on the overall system configuration

Finally, as far as cost is concerned it is obvious that the current system is probably the least expensive. However, if an all electric engine is to be implemented, then the costs of an electrically driven afterburner will be minimal compared to the total costs of the new design. The same holds true in the case of and air turbine.

6.0 FURTHER WORK.

Clearly, solutions that are light in weight, small in size, and have the least impact on thrust output from the engine are the most favourable. This paper has looked at an air turbine that is driven by bleed air from the engine. Further work could include:

- Determining whether it is possible to control the bleed to the amounts specified,
- A 3-d design analysis on feasible models,
- Other volute geometries

Using bleed air from both the engine and from ram air at the intake. Firstly, during the development of this study, specific amounts of bleed (i.e. 0.9 $kg \cdot s^{-1}$) were used to see the effects on the rotor design. In practice, it is unclear whether the valves and control system can control the specific amounts of bleed sufficiently accurately. Accordingly possible fluctuations in bleed flow should be determined. If large fluctuations occur, the off-design performance will be more critical to ensure proper power generation.

If an air turbine is ever to be used to drive the fuel pump, a 3-d fluid dynamics analysis will have to be done. This analysis should include a reliability analysis to ensure that the transient thermal stresses are acceptable based on the temperature gradients.

The third suggestion is to accept a less efficient volute geometry, i.e. to reduce the outer diameter (a triangular section shown on Figure 3.5). This is concluded from the performance data at Mach 2.0 (5000 m). There is significant ram pressure and temperature in the intake to power the air turbine. Instead of bleeding more air off the engine when high Mach numbers are achieved, air could be bled out of the intake system to provide a higher mass flow to the air turbine. The disadvantage is the increasing complication in the ducting and the doors that will be required in the intake. In addition, bleed air will still be necessary off the engine, since at lower speeds there will be little or no ram air to pull from the intake. At higher speeds, however, it does have the advantage of not affecting the engine as much as increasing the amount of mass flow taken from the engine.

Future work currently encompasses the publication of the a comparative study dealing with the energetic performance of the three designs and their effects on the performance of the engine/aircraft system.

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