MICRO PROPULSION ACTIVITIES AT THE UNIVERSITY OF SYDNEY

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Abstract: At the moment there are no relatively small unmanned aircraft for flights above 15000 ft, due to the lack of an appropriate propulsion system. If a reasonable efficiency can be attained, small turboprop engines could enable filling this gap. A careful design and optimization of components is however a must to counteract the drop in efficiency encountered when reducing the size of gas turbines. The current paper describes results from reversed engineering on the KJ66 micro gas turbine. It is shown that the efficiencies of each of the components can be improved by several percent. A curved vane diffuser for instance increases the compressor efficiency by 2 to 6%. Turbine separation can on the other hand be suppressed by adding a spherical dimple vortex generator.

Keywords: unmanned aerial vehicles, micro gas turbines, component optimization, compressor, turbine

INTRODUCTION

A wide range of unmanned aerial vehicles (UAVs) is currently operated worldwide. At the moment there are however no relatively small platforms for medium to high altitude flight, mainly due to the lack of an appropriate propulsion system for these types of missions. Intermittent combustion (piston) engines currently used on UAVs limit operations to roughly 15000 ft seen the significant drop in power output and rise in specific fuel consumption at altitude [19]. The power density of electrical power trains on the other hand prevents the use of small platforms for endurances of several hours [9].

Provided that a reasonable efficiency can be attained, small or micro turboprop engines therefore seem the most adequate propulsion system to enable small platforms flying at altitudes exceeding 15000 ft. Engines of the appropriate size and efficiency are nevertheless not available at the moment. The smallest gas turbines available from the aircraft engine manufacturers are on the one hand too big and heavy, whereas efficiency of the turbojet or turboprop engines in the hobby market is too low to be acceptable for the intended application, partially since fuel efficiency is usually neglected in favor of affordability and ease of construction and operation [8].

The low efficiencies are however also inherent to small gas turbines seen their high rotational speed, low Reynolds number turbomachinery and low volume combustion chambers [1,13,14,20]. Most of the issues prohibiting efficient micro gas turbines are further aggravated at high altitudes and systematic research into the effect on engine performance is therefore required. To undertake this research The University of Sydney created the Micro Propulsion Group (MPG).

This paper presents the activities of the MPG on small gas turbine engines. A first introductory section of the paper will briefly review the challenges faced when scaling down gas turbine engines. In a next section, the results of an extensive "reversed engineering" activity on existing hobby market engines of the appropriate size will be shown and the main areas of improvement will be identified for each of the components.

CHALLENGES OF SCALING DOWN GAS TURBINES

Reducing the size of gas turbine components to a centimeter or even millimeter scale leads to several new design issues that are not present in larger size machines. Because of the small size, micro jet engines exhibit very small airflow rates, low component pressure ratios and Reynolds numbers and very high rotational speed. All of these lead to a reduction in efficiency of the individual components and of the overall cycle.

The low mass flow rates and Reynolds numbers impose severe limitations on the achievable compressor efficiencies. The influence of Reynolds number and mass flow can be assessed using the following equation [7]:

$$\frac{1-\eta_{pol}}{1-\eta_{pol}^{*}} = \left(\frac{\dot{m}}{\dot{m}^{*}}\right)^{-m} \cdot \left(\frac{\mathrm{Re}}{\mathrm{Re}^{*}}\right)^{-n}$$

with η_{pol} the polytropic efficiency, $\dot{m}$ the mass flow rate through the compressor and Re the Reynolds number. The superscript * indicates reference conditions, which are takes as 70 kg/s for the mass flow rate, 10^7 for Re and 0.905 for η_{pol} [7]. For centrifugal compressors, the exponents m and n are 0.063 and 0.1 respectively [7]. With a mass flow rate of 0.25 kg/s and a Reynolds number of 500000, both typical values for micro gas turbines of the model market [3,8,11,12,15,21], the polytropic compressor efficiency reduces to .801 or a reduction of over 10%. For pressure ratios around 2.5 this equates to an isentropic efficiency around 77%.

A further reduction in efficiency, in addition to the aforementioned effects, can be expected when scaling down the compressor due to the increased importance of tip clearance effects, as shown by the following equation from [13]:

$$\frac{\Delta\eta_{pol}}{\eta_{pol}} = k \cdot \frac{t}{h}$$

where t is the tip clearance and h is the height of the blade. A common value for the constant k for large scale compressors is 0.3, whereas experiments show that for ultra micro gas turbines in the millimeter scale range the value of k increases to around 0.65 [13]. Not only will the relative tip clearance be higher at smaller scales, its influence on the polytropic efficiency is also about twice as big. This indicates that tight geometric clearances between rotating and stationary parts are crucial to inhibit excessive fluid leakage and the corresponding losses. As a consequence, the compressor isentropic efficiency drops to values around 70-75%, which is in line with the values obtained in [5,11,15,16].

Due to the decreasing Reynolds number and the large relative clearances, a higher blade tip speed is needed to yield the same compressor pressure ratio [14]. With a rotor diameter of a few centimeters, typical rotational speeds lie between 100000 and 250000 rpm, which requires new bearing technologies to obtain a reasonable lifetime and mean time between overhaul (MTBO) [14]. The hobby market engines, where ceramic ball bearings are typically used, have MTBO's in the order of 25 hours, which is clearly not acceptable for "professional" usage. Foil bearings and hybrid bearings seem to be the most promising technologies for gas turbines of this size as they are relatively stable and offer minimal bearing losses [14]. In small machines with a limited power output, excessive frictional power loss within the bearing will after all result in a severe penalty on cycle efficiency.

Even though the Reynolds number in the turbine is an order of magnitude smaller than in the compressor (14000 to 32000 [3,4]), its effect on the turbine efficiency is less pronounced due to the favourable pressure gradient. As a consequence the turbine efficiency is about 5-10% higher than the compressor efficiency and values around 75-80% are typical [5,14,15,17]. The low Reynolds number on the turbine blades however leads to mostly laminar or transitional flow and as a consequence the turbine is more susceptible to flow separation [3,4].

Similar to the turbomachinery efficiency reduction, combustion chamber efficiencies of small gas turbines are typically several percent lower than those of the large counterparts. The higher surface-to-volume ratio of small combustion chambers namely leads to large heat losses [13,17]. For millimeter size combustion chambers, heat losses can mount up to 25% of the energy of the fuel [13]. The flow laminarization and the shortened diffusion characteristics of mass and heat lead on the other hand to difficult mixing of fuel and air, resulting in poor flame stability and hot spots in the combustion chamber exit flow [13,17]. This has significant implications on both the life of the turbine and the power output and cycle efficiency.

Finally, the small size of the components leads to significant inter-component heat transfer. The viscous forces inside the machine are much larger than for large gas turbines due to the lower Reynolds numbers, resulting in fluid film heat transfer coefficients that are higher by a factor of about 3 [17]. Thus, the temperature gradients within the structure are reduced, which makes thermal insulation critical. Heat transfer namely leads to cooling of the turbine and heating of the compressor with a corresponding efficiency drop for both components [20]. For instance, the temperature rise due to heat transfer in IHI Dynajet compressor leads to a compressor exit temperature that is 11.5% higher than for an adiabatic compressor, or a heat addition equal to 25.4% of the shaft power [12]. This equates to a reduction in compressor isentropic efficiency of 6-8% [12,20]. For simple gas turbine cycles, the effect on cycle efficiency is slightly compensated as the higher compressor exit temperature slightly reduces the required fuel flow for a given turbine inlet temperature [20]. The impact on power output is however severe and as a consequence a larger gas turbine is needed.

REVERSED ENGINEERING OF EXISTING HOBBY MARKET ENGINES

Several small gas turbines are available for recreational model aircraft. Since a lot of trial and error has led to the development of these model aircraft engines, they represent a good point of departure for a reversed engineering. As plenty of empirical data as well as the technical plans of the KJ66 are available in the public domain [8], this engine has been selected for our analysis and optimization. The KJ66 has a centrifugal compressor with a rotor diameter of 66mm, an annular combustion chamber and an axial turbine. The engine has an outer diameter of 108 mm and delivers 92N of thrust at a speed of 128000 rpm [3,11]

Compressor

As most of the hobby market gas turbines, the KJ66 employs a compressor wheel from a car turbocharger, the Turbolader-Schwitzer KKK2038 [11]. In the KJ66 engine this wheel is coupled to a wedge diffuser, as shown on Figure 1.

Our analysis of the original compressor showed that the largest source of inefficiency for this particular compressor was located in the wedge diffuser. The diffuser was therefore redesigned with curved annular vanes for which streamlines are shown on Figure 2. The curved diffuser lead to an increase in isentropic compressor efficiency ranging from 2% at 120000 rpm to about 6% at 80000 rpm [11]. An increase in stable operating mass flow range was also observed at the expense of a slight drop in pressure ratio [11].

To compensate for the small reduction in pressure ratio, the wheel outer diameter was increased to 70 mm

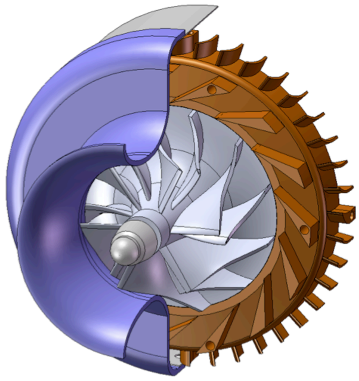


Figure 1: The original KJ66 compressor [11]

without changing the outer diameter of the engine. This lead to an increase in pressure ratio between 3 to 5% over the original wedge diffuser for the analyzed operating range while keeping the efficiency at the levels of the curved vane diffuser [11].

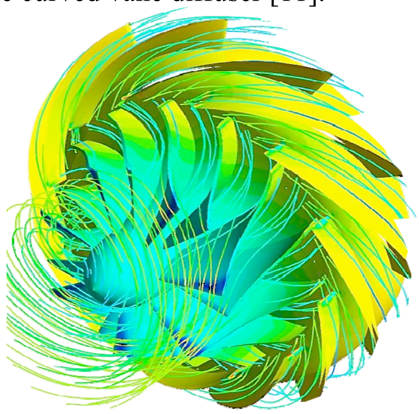


Figure 2: Streamlines for the curved vaned diffuser [11]

Combustion chamber

The combustion chamber of the KJ66 features direct fuel injection with 6 vaporizing sticks to ensure complete combustion inside the chamber. The combustion chamber pressure drop is around 12% of the compressor delivery pressure and the exit temperature at approximately 120000rpm lies between 920 and 980 K. The combustion chamber was analyzed through CFD using 6 different turbulence models (see [6] for details). The LES with a wall adapted local eddy viscosity (WALE) sub-grid model proved to be the most accurate in comparison with experimental data. Results of the LES-WALE calculations are shown on Figure 3.

The top part of figure 3 shows the temperatures of a cut through the combustion chamber at the location of the vaporizing stick. The bottom section shows the temperatures at the outlet of the chamber. As shown, the temperature profile is very non-uniform, resulting in strong performance and lifetime reductions for the turbine.

Turbine

Reversed engineering of the axial turbine of the KJ66 revealed that flow separation at the low operating Reynolds number is the main reason for the relatively low efficiency [3,4].

As shown on Figure 4(a), separation occurs at

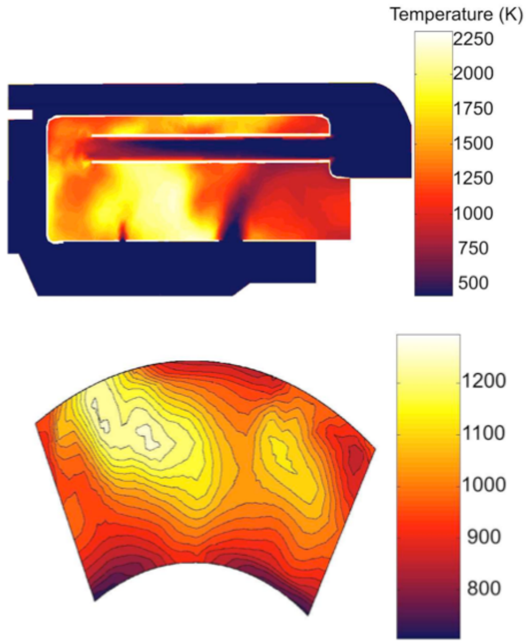
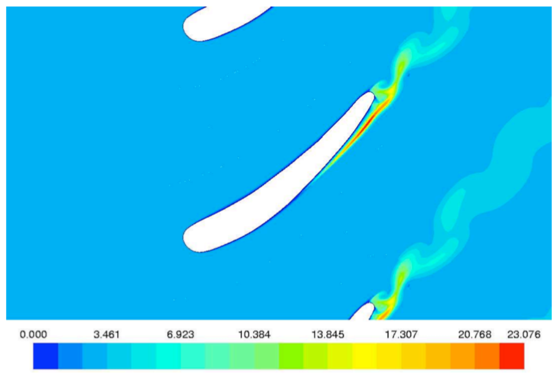
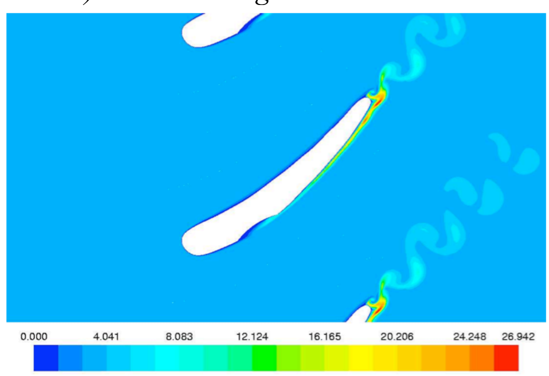


Figure 3: Reynolds averaged temperatures of the combustion chamber [6]

approximately 60% of the blade length. Based on research on low-pressure turbine blades [10], a spherical dimple vortex generator was added to the blade profile to delay this separation. As indicated by Figure 4(b), this simple device results in improved flow attachment over most of the turbine blade.



a) Original turbine blade



b) Turbine blade with vortex generator

Figure 4. Instantaneous turbulent kinetic energy contours at Re 230000 [3]

CONCLUSION

At the moment there are no relatively small UAVs for medium to high altitude flight, due to the lack of an appropriate propulsion system. Provided that a reasonable efficiency can be attained, small or micro turboprop engines could enable filling this gap. Reducing the size of gas turbines to the centimeter range however inherently leads to efficiency reductions and a careful design and optimization of components is therefore a must.

Reversed engineering of the KJ66 micro gas turbine for model aircraft shows that the efficiencies of each of the components can be improved by several percent. A curved vane diffuser for instance increases the compressor efficiency by 2 to 6%. Turbine separation can on the other hand be suppressed by adding a spherical dimple vortex generator. The combined effect of each of these measures results in a considerable improvement of the overall cycle.

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