Micro Turbines from the Standpoint of Potential Users

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This paper describes some micro turbine aspects from the standpoint of potential users. First, some of the pros and the cons of small gas turbines compared to other competing technologies are given. The discussed aspects are mainly focussed on technical advantages and disadvantages as it is hard to predict how fast and to what extent the different technologies (including that of mini gas turbines) will mature. Even though the final applications will obviously strongly depend upon the economical benefits that the technology would offer, an economical comparison is not made here. Therefore the comparison made throughout this contribution remains relatively general.

Once the pros and the cons are discussed, some potential applications are described. The possible applications are divided into two different categories: power generation for portable devices and vehicle propulsion. For each class of applications some examples are given. Finally, then, some conclusions are drawn.

1 PROS AND CONS FOR SMALL GAS TURBINE ENGINES

Before turning our attention to potential applications for small gas turbines a comparison is made with existing small power generating and storage systems as batteries and to a smaller extent also fuel cells. After all, in an economy-driven market a new system can only be introduced when it offers some benefits (operational, functional or economical) compared to existing systems. First the possible advantages of small gas turbines will be discussed. Then some of the disadvantages will be dealt with. As it is hard to predict how the different competing technologies will mature an economical comparison is not performed here.

1.1 Advantages of Small Gas Turbines

The main advantage of small gas turbine engines over existing power supply systems lies in the high energy density potential of the fuel-based systems. Even with relatively low overall system efficiency the power per unit of weight of a gas turbine system will be much higher compared to existing or in the near future available batteries thus reducing the overall system weight significantly for missions requiring a high power output and a long duration. However, due to the scaling towards smaller sizes, a micro gas turbine could also offer an advantage for the system redundancy and reliability as well as for the operational flexibility. Both effects will be explained below.

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1.1.1 High Energy Density Potential

The main advantage of a small gas turbine over a pack of batteries lies in the high specific energy potential of the gas turbine concept. As a matter of fact, the energy density of hydrocarbon and hydrogen based fuels far exceeds that of state of the art batteries. For instance, current state of the art rechargeable batteries have an energy density around 100 – 150 Whr/kg while primary cells typically attain twice that value. However, theoretically the highest attainable energy density lies around 1400 – 2000 Whr/kg for lithium based systems, where the lower realized performance is primarily due to safety considerations (ref. [1]).

Nevertheless, even though a higher energy density for batteries is thus feasible in the near future, the potential of a fuel-based power generating system is much higher as can be seen from Figure 1. On that figure the energy density of some typical state of the art batteries is compared to a power generating system based on fuel with an overall system efficiency of 10%. Even with a relatively low overall system efficiency, fuel-based power generating systems have an energy density that is at least equivalent to the theoretical potential of lithium based batteries.

Obviously, in this comparison, normally, the weight of the engine, fuel tank and other system components should also be included which will slightly change the global picture. For hydrogen the impact will however be slightly higher than for the other fuels as it needs to be stored as either a cryogenic fuel or as a gas under high pressure. For both cases a somewhat higher fuel tank weight will result (due to either the insulation or the big walls needed to withstand the pressure). The use of composites in the tanks will however limit this disadvantage. However, as the engine weight will normally be small for micro gas turbines, it will only be important if it represents a significant portion of the overall system mass. This will not be the case for long term operations where the fuel weight will be the dominant factor. Figure 1 (derived from ref. [6]) is thus mainly applicable to utilization for a long duration.

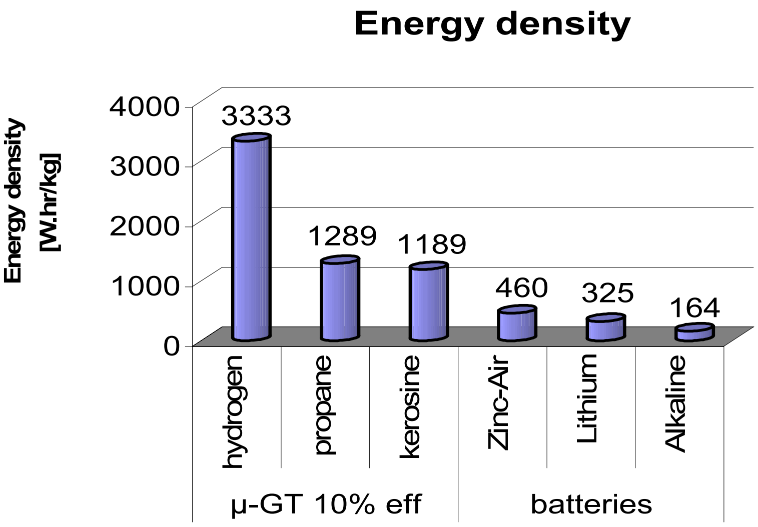

Figure 1: A Comparison of the Energy Densities of Micro Gas Turbines and Batteries.

From Figure 1, one could nevertheless conclude that hydrogen offers the biggest potential for use in small gas turbine engines due to its high energy density. On top of that, the properties of hydrogen also make it an attractive choice as a fuel. However, this is only true if the system is weight-limited. If the volume occupied by the system is an important issue, the low density of hydrogen will be a big disadvantage despite its high energy content. The density of liquid hydrogen is only approximately 10 % of that of hydrocarbon fuels. On top of that the use of hydrogen also brings along some serious safety considerations due to the wide flammability limits and the low ignition energy needed. In order to get a high weight and volume energy density a hydrocarbon fuel would thus be needed with propane as the most promising alternative due to its compromise between a good stability characteristic and a high energy density (ref. [3]).

Besides the energy density advantage, the fuel-based power generating systems also have a power density advantage (see Figure 2). The higher energy density batteries normally have high impedance too. Because of that high impedance, a relatively long period is needed to withdraw the energy from the battery. For applications involving high current draws and kilowatt-size electrical motors, such as vehicle starting and portable electrical tools, a micro gas turbine could provide a quite good alternative (ref. [1]). On top of that, batteries naturally discharge over time while a fuel provides a long storage time without the loss of potency. This is not totally correct for hydrogen. Due to the cryogenic storage hydrogen will lose some of its mass and thus potential over time through boil-off.

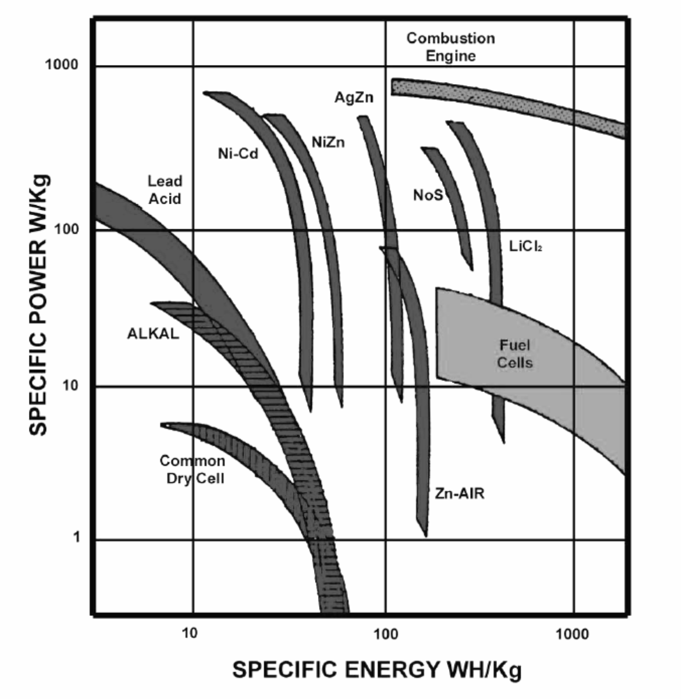

Figure 2: Power Density versus Energy Density for Different Alternatives (ref. [4]).

As can be seen from this figure, combustion engines in general, and thus also gas turbines in particular, offer a distinct advantage over other existing power generating systems. The main competing technology for combustion engines in the high specific energy regime seems to be fuel cell applications. However, due to the relatively high system weight (fuel cell and, if applicable, fuel converter weight) inherent to this technology, fuel cells only have moderate power densities compared to combustion based systems which leads to a slightly higher system weight. This is also shown on Figure 3. From that figure one can conclude that micro heat engines will offer the smallest system weight for missions requiring a high energy.

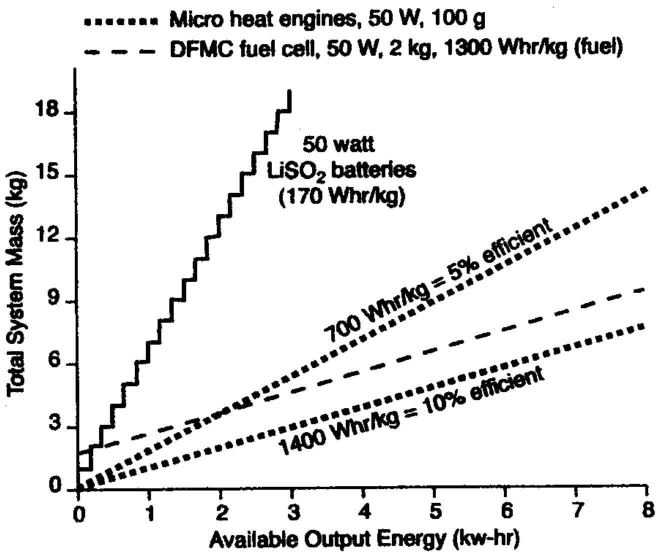

Figure 3: Comparison of Micro Heat Engines with Fuel Cells and Batteries (ref. [1]).

Obviously, a gas turbine is not the only possible micro heat engine application that is envisaged. Several other "concepts" such as micro internal combustion engines, micro Wankel and Stirling engine, etc. are also being investigated across the world. As all these "concepts" are based on the generation of power from the combustion of a fuel, the pros and the cons are generally the same for the different systems. The final outcome of the several designs (efficiency, size, etc.) will according to the author, determine what system will be the most attractive for a given application. Today, the different technologies are however not mature enough to give some explicit guidelines.

1.1.2 Increased Redundancy and Reliability

Intrinsically, powerMEMS and more specifically micro gas turbines benefit from their small scale. Neglecting the increased relative heat loss and the lower attainable efficiency, one can show that the power per engine volume of a gas turbine scales inversely with the density for geometrically identical engines (ref. [2]).

$$\frac{P}{V} \propto \frac{1}{L}$$

where P is the power output of the engine, V is the engine volume and L is the length scale of the engine. Obviously the higher heat losses and lower component efficiencies will tend to flatting out this trend. However, compared to large gas turbines, a reduction in scale will lead to a higher power per unit of volume until a certain optimum scale is attained.

Let us now image two geometrically identical engines operating under the same cycle conditions (pressures and temperatures). If the scale of engine b is 4 times smaller than the scale of engine a, engine b delivers theoretically only a sixteenth of the power of engine a. As a matter of fact, assuming that the operational conditions remain the same for both engines, the power of the engine scales with the mass flow through it. This mass flow on its turn scales with the inlet area or thus with the second power of the scale factor. In other words theoretically one would need 16 small engines to deliver the same power of one big engine. However, these 16 engines only take up a fourth of the volume of the big engine seen that volume scales with the scale factor to the third power. If one now assumes that the power output of the small engine is reduced by a factor of two due to the higher heat losses and the lower component efficiencies, one only needs half the volume needed by the big engine to produce the same power. A part of this volume gain could then be used to add some extra small engines to provide redundancy and higher system reliability. If we would add four redundant small engines, the overall system only fails when the fifth engine fails.

Besides the extra redundancy provided and the volume reduction, another advantage of using a "stack" of small engines is the possible decentralization of the power production (ref. [7]). Several of the small engines could be located at their optimum position, reducing the system piping, etc. Finally, the system of several small engines will also provide a better efficiency at part load. For a single engine system, part load operation is namely only possible by going towards lower regimes (lower TIT and RPM) which automatically reduces the efficiency of the engine. When using several small engines, however, one could shut down some of the engines to match the reduced power required. The rest of the engines could then work at full power and thus near maximum efficiency which leads to a higher overall system efficiency at part load.

1.1.2 Increased Operational Flexibility

Besides the higher energy density potential and the added reliability and redundancy, micro gas turbines could also add to the operational flexibility of portable power systems compared to battery-powered systems. When using a battery one can only achieve a high operational flexibility when carrying extra heavy sets of batteries to fill the gap when recharging the "main" battery which leads to a considerable increase in the overall system weight. If one would want to keep this weight down by omitting this spare battery, the system will be less flexible, because the user will have to wait while the battery is recharging.

When using fuel-based power sources as micro gas turbines however, one could easily click in a new "cartridge" of fuel when the original one is empty. Obviously this also adds some weight to the overall system. This extra weight will however be much lower than for the battery-powered system seen the high energy density of the system (see Figure 3) and the possibility to use composite fuel tanks. For some applications one could also use a big central tank to power several small engines at the same time.

1.2 Disadvantages of Small Gas Turbines

The main disadvantage of micro heat engines compared to batteries and some other power generating systems as fuel cells lies in the high overall temperature of the system. In order to get a high power output, a high turbine inlet temperature[1] is needed. Given the small scale of the engines, this high TIT will lead to a high overall temperature of the engine structure which implies a significant infrared signature which could be important for some military applications (see later on). Fuel cells, only suffer from this phenomenon to a smaller extent because of their lower operating temperatures[2].

However, the infrared signature is not the only disadvantage of the high overall temperature of the engine structure. Several safety measurements will be needed as well. This situation is even further aggravated by the high temperature of the exhaust gasses. However, the exhaust gas temperature can be reduced by the incorporation of a recuperator in the engine cycle and some of the energy of the high temperature exhaust gasses and walls could be re-used by taking advantage of the Peltier effect to cool the engine structure and/or the gasses and at the same time further increase the power output of the device. Nevertheless, the

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[1] The Turbine Inlet Temperature or TIT is the total temperature obtained just in front of the turbine.

[2] For instance, for Solid Oxide Fuel Cells (SOFC) the operating temperature is in the range of 900 – 1000 °C which is close to the TIT of a small micro gas turbine. However, a Proton Exchange Membrane (PEMFC) or a Direct Methanol fuel cell (DMFC) for instance works at a much lower temperatures of about 90 to 130 °C respectively.

overall temperature will be high compared to the typical operating temperature of PEM or even SOFC which could mean a significant advantage for the latter technology.

Besides the disadvantage of the high temperature and the safety problems associated with this, combustion based air-breathing engines also suffer from exhaust gas contaminations preventing the indoor use of these systems in environments with little ventilation. The requirement for continuous air flows could also limit the applicability of the system as well as problems associated with noise. Finally, some logistic problems can also be associated with the use of fuel in remote locations. Obviously, micro heat engines will thus require a significant improvement of the overall system efficiency before some of the problems associated with its use will be mitigated.

2 POTENTIAL APPLICATIONS FOR MICRO GAS TURBINES

Several applications for micro gas turbines can easily be envisaged. In general, they can be divided into two groups. On the one hand there are applications where the gas turbine is used as a portable power generating system. Besides this, the gas turbine can also be used for the production of thrust or power to propel a vehicle. First, the power generation applications are discussed. Then, the attention is turned towards the propulsion of air vehicles.

2.1 Portable Power Generation

As already explained before, the main advantage of fuel-based systems in general and micro gas turbine engines in particular, lies in the high attainable power and energy density compared to batteries. However, several safety aspects will limit the applicability of micro gas turbines, at least at short term, to environments where safety is already a key issue like military or construction/building sites. The possible applications for civil every day use thus seem somehow limited. Nevertheless, some applications could be imagined. First, some of the military power generation applications are discussed. Then, some possible applications for civil operations are elucidated.

2.1.1 Military Applications

Nowadays, electronics are critical to soldier combat effectiveness with primary batteries as the main energy source. However, the acquisition, storage, distribution and disposal of several types of batteries pose an enormous logistical challenge on the battlefield. New technologies have at the same time increased the number and variety of power-driven functions that require soldier-portable power (for night-vision and infrared sights, computer displays, communications, etc.). Due to this high power demand and the low energy density of batteries, the physical load borne by a dismounted soldier can exceed 100 pounds for certain missions (ref. [4]). Micro gas turbines could help to reduce this load which implies the potential of a very large production market. On top of that, several military applications could also be envisaged with a new power source because they fill the gap where batteries are not very well suited. Some of these potential applications are shown on Figure 4.

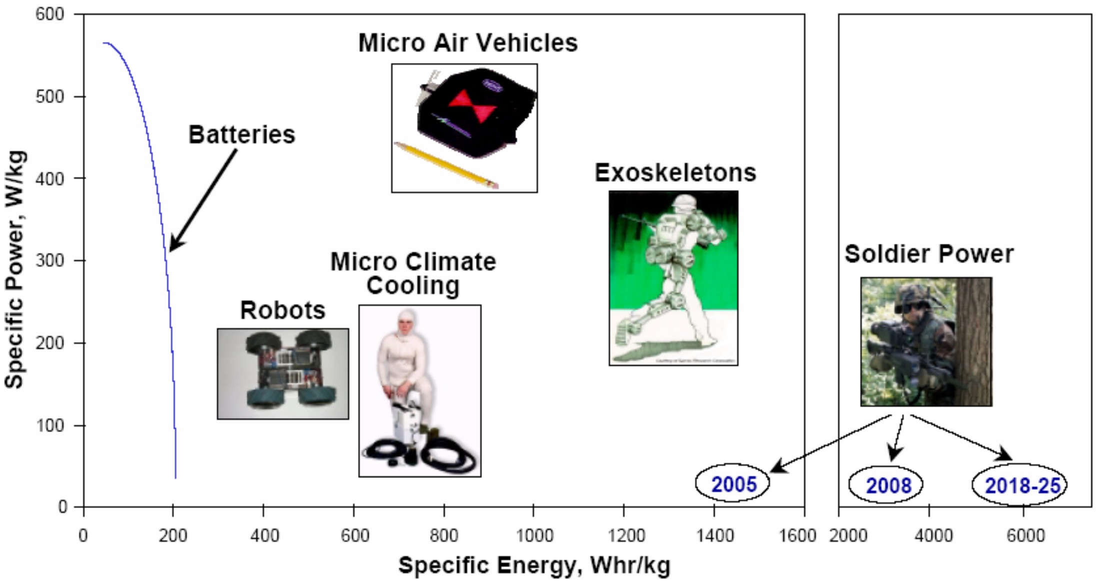

Figure 4: Performance Shortfall of Today's Power Sources (ref. [5]).

In order to reduce the physical load for long duration missions or to allow some "new" applications, a new power source with an increased energy density is thus needed with an ultra micro gas turbine as one of the possible alternatives. In general, according to DARPA, there are three separate regimes for future army applications: 20 W average with a 50 W peak, 100 W average with a 200 W peak and 1 to 5 kW high power draw applications (ref. [4]).

The 20 W regime was assumed to cover power solutions for computers, radios, sensors and displays. The 100 W regime would allow applications such as a laser target designator and microclimate cooling (ventilation for soldiers wearing protective clothing). A portable recharger for rechargeable batteries would also fall in this regime. Finally, the 1 to 5 kW regime includes power-intensive capabilities such as exoskeletons. Exoskeletons are robotic human performance augmentation systems which, for instance, artificially reduce the load felt by the soldier. Some possible applications for these different regimes are shown on Figure 5. On the left top side of the Figure two applications for the 20 W regime are shown: a military portable digital assistant (PDA) and a walky-talky. The right top side of the figure on the other hand shows a possible portable battery recharger unit, an application of the 100 W regime. Finally the bottom of the figure shows two exoskeleton applications where a robotic system is used to reduce the load of a soldier respectively nurse.

Figure 5: Some Possible Military Applications for Micro Gas Turbines.

2.1.2 Civil Applications

As already mentioned, civil applications of the micro gas turbine as a power generating system will undoubtedly be limited by the high temperatures inherent in the system and the safety problems associated with this (especially with the hot exhaust gasses). The envisaged applications should therefore, at least in the short term, be limited to safety controlled environments such as hospitals and construction sites. As fuel cells also offer a high energy density and only suffer to a lesser extent from this type of safety issues, this market segment will most probably be filled with fuel cell applications rather than micro heat engines. Nevertheless, some potential applications are shown on Figure 6.

Figure 6: Some Possible Civil Applications.

On the left hand side of the figure a cordless drill is shown while the right hand side shows a recharging unit for a cell phone battery. Obviously, if the safety problems can be overcome, a notebook or a PDA could also be powered (directly or indirectly through a battery recharging system) by a micro gas turbine. Portable tools such as drills but also large mixers or sawing machines certainly offer a broad potential market.

2.2 Vehicle Propulsion

As already mentioned, micro gas turbines are also very well suited for vehicle propulsion. In general, one could foresee two classes of applications in this field: the propulsion of micro aerial vehicles (MAV) on the one hand and the so-called distributed propulsion where several small engines are used to propel a large unmanned vehicle or a small manned aircraft on the other hand. Both classes of applications will be discussed. First MAV propulsion is treated. Then, distributed propulsion systems are very briefly reviewed.

2.2.1 Micro Aerial Vehicles (MAV)

Following the successes of the so-called *tactical* Unmanned Aerial Vehicles (UAV), used in the Balkans, in Afghanistan and in Iraq, military commanders of lower echelons have expressed the need of having their own UAV system (ref. [9]). However, the flight speed, complexity and cost of UAV systems used at the brigade and division levels, are relatively high. Commanders of the battalion or the company and even the platoon leaders, need what is called situational awareness. This is the reason why micro and mini UAVs, known by the acronym *MAV* are currently under development. If used for observation purposes, they can be looked at flying binoculars. In the past there has been a lot of confusion about the definition of micro and mini systems. Currently it is commonly accepted that a micro UAV is a flying asset having dimensions less than 6 inches (15 cm) in any direction. MAVs larger than 15 cm, but still *packpack portable* are called mini-UAVs.

Both have the capability of performing a military mission at an affordable cost. They carry a miniaturized payload, a communication link and are equipped with a fully autonomous navigation system. MAVs may weigh as little as 50 grams. As a result of its small size and low required power, MAVs will be very suitable for covert operations. In flight the human eye would see a MAV as a bird and also the MAV's radar signature will be comparable to that of birds. Therefore this signature will disappear in the background noise. The velocity of a MAV will be about 10 to 20 m/s, thus below the detectable level of actual radars. Even infrared detection will not be easy to obtain, because of the low power required by the propulsion system.

Military applications (Figures 7 and 8) include *looking over the hill* or *over the obstacle*, reconnaissance and surveillance, targeting identification, sensor emplacement, sensing of nuclear, biological and chemical contaminants, urban war fighting. Range is of the order of 5 to 10 km while the endurance should be between 20 and 60 minutes. Civil operations such as counter drug support, police assistance in cases of criminal actions, assistance in finding survivors after disasters like earthquakes, and in the domain of security tasks, are also potential applications.

Looking over the Hill (LoH) **Looking over the Obstacle (LoO)**

Figure 7: Typical MAV Missions.

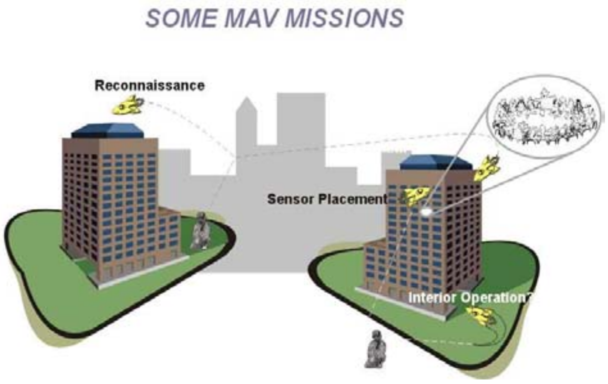

Figure 8: Sensor Emplacement and Interior Operation.

A MAV could also be developed for interior operations. However in this case the data link between the micro-aircraft and its base station may be interrupted. For indoor operations, the MAV should therefore be equipped with an onboard navigation system and with memory to store the intelligence data as long as the line of sight communication is not re-established. For operations in interior spaces, the MAV should be able to land and shut down its propulsion system autonomously, and to take off again once a door or a window is opening. Another idea is to give the MAV a feature to turn into a crawler, giving it a possibility for hiding itself, finding a way for escaping, or for local sensing.

2.2.1.1 Challenges

Aerodynamics

One of the most important challenges is the physics of aerodynamics for flying, flight stabilization and control. Figure 9 shows the relation between the gross weight and the Reynolds number, for an airliner, an advanced fighter, a small plane, two UAVs, small birds and the dragonfly. On the same graph, the region is shadowed wherein the MAVs will operate. At these low Re values airfoil performance is still not well understood and research in this field is accelerating since only a few years, both in the theoretical and in the experimental fields (ref. [10] and [11]). Unfamiliar flying techniques are considered as well. For this reason the morphology and the way small birds and insects are flying is currently analyzed in detail.

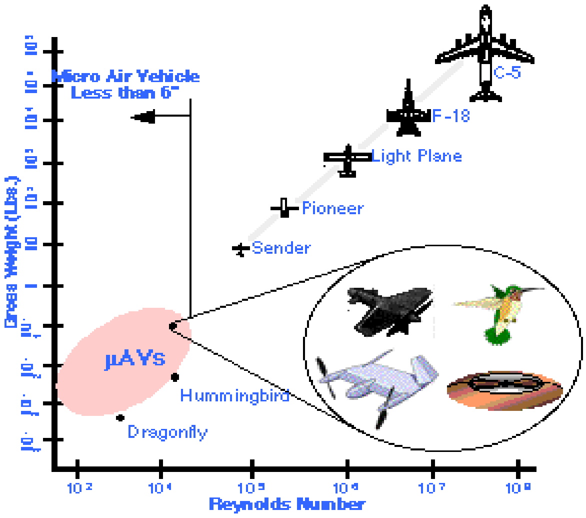

Figure 9: Gross Weight and Reynolds Number.

Propulsion

Another challenge concerns propulsion. Very compact, lightweight, high power and high energy density propulsion systems are required. A MAV will require about 2.5 W of shaft power for cruise and twice as much during climbing and manoeuvring. The simplest propulsion system is obviously a battery-driven electric motor. One important problem is the limited discharge rate, another is the low energy density. The energy stored per unit mass of a lithium battery is very low compared with the energy of one gram of liquid fuel. However, it is expected that in the coming years the following goals will be attained: a power density of 350 mW/g for an energy density of 800 J/g. Thermal cycle machines of all types are presently studied, both theoretically and experimentally. Unfortunately, conventional internal combustion engines of such a small size have limited thermal efficiency (about 5%), but power densities of 1 W/g can be achieved.

Figure 10 shows an example of an electric driven MAV.

Figure 10: Birdy MAV (Property of the first author).

Other Challenges

Other challenges include micro-gyros, lightweight communication and navigation equipment as well as sensor systems consuming as little energy as possible, collision avoidance and collision recovery technology, flight control components such as piezoelectric actuators and small inertial angular rate sensors.

As this paper is intended for the aeronautic and turbomachinery communities, I deliberately discarded a discussion on advanced sensors. However, this is obviously a key element in the success of MAVs. Imaging sensors, for instance, capable of detecting personnel, need focal planes with about 1000x1000 pixels when flown at an altitude of 100 m. The goal is a 100mW camera of only some grams.

Of course all this equipment increases the weight of the MAV and demands additional power to function. Increasing weight means also better performing propulsion systems to fulfil the mission. For all these reasons MAVs are really waiting for micro gas turbine engines to mature.

2.2.1.2 Conclusions

What the future looks like for MAVs is still difficult to foresee. However, in this particular field there is a lot of outstanding research work going on. My personal view is that by the end of this decade several MAVs will be at the stage of operational use.

2.2.2 Distributed Propulsion

Distributed engines are decentralized propulsion systems that utilize smaller powerplants that are deployed over (or embedded into) the aircraft. Examples of this type of propulsion system might include small or mini engines deployed across the wingspan and fuselage, and micro-turbine engines embedded in the aircraft surface for flow/circulation-control and thrust (Figure 11).

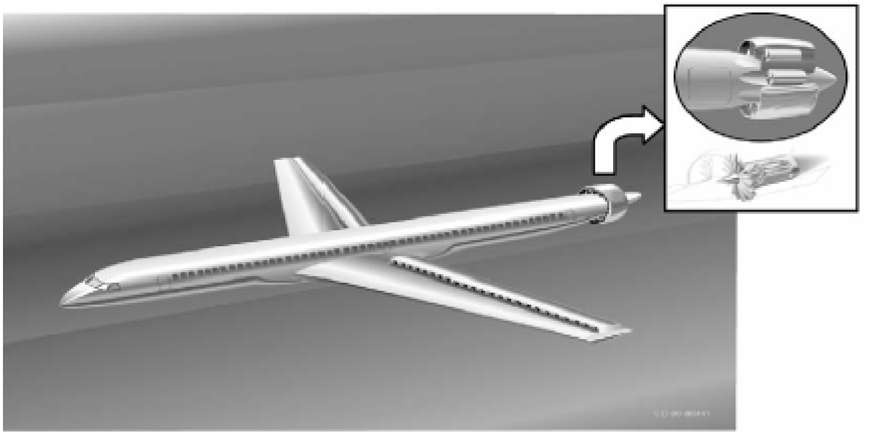

Figure 11: Distributed Engines embedded in the Wing and Body (ref. [8]).

For this type of applications, performance penalties associated with mini-engine systems principally are due to boundary layer effects of the fluid being on the same geometric scale as the propulsion system. The challenge of manufacturing tolerances that can be met economically in these engines will also impact their performance and thus cost. Therefore, as for every application, mini- and micro- engine propulsion systems must provide benefits that offset these performance and cost penalties compared to the classical aircraft layout. Such could include noise and drag reduction, a superior integrated aircraft/engine system, and reduced acquisition cost (through high-volume production). Laterally distributed engines will afford similar aerodynamic and acoustic benefits as those described for the high-aspect-ratio wing trailing edge nozzle (ref. [8]). Additional aircraft integration of supporting fluidic technologies using distributed engines could provide more dramatic transport mission impacts. Systems studies have shown that as much as 3 – 5% of total aircraft fuel burn reduction might be realized from boundary layer ingestion by employing small- to mini-engine distributed propulsion systems (ref. [8]). This performance benefit may be enhanced in a hybrid system utilizing micro engines to energize the low-momentum boundary layer flow. This benefit obviously only can be realized if the micro-engine fuel consumption is low.

3. CONCLUSIONS

Even though it is very difficult to predict the near future (let alone the far future) it is shown here that there is a relatively big potential market for micro gas turbines due to the high specific energy and power inherent in the system. However, some safety issues, mainly related to the high temperature levels obtained in these micro devices, still need to be overcome. The system efficiency attained for a mature technology level will be a key issues in the determination of which power source is the best suited one for a particular application.

However, when micro gas turbines obtain efficiencies higher than or similar to the competing technologies, several fields of applications can be envisaged. A micro gas turbine could namely be used both for the generation of the power required for several portable systems (military and/or civil) as well as for the propulsion of aerial vehicles.

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