Chapter 11
Design and Development of Small Engines for UAV Applications

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Abstract Unmanned Aerial Vehicles (UAVs) have been extensively used for a wide range of applications since World War-II. UAVs are used for several defence purposes such as surveillance, communication, terrain mapping, reconnaissance, and attack. In this chapter, we discuss reciprocating internal combustion engine as a propulsion system for UAVs and the challenges in development of such an engine for aviation. The reciprocating piston engine is one of the most effective powerplants to energise the UAVs. The purpose of these propulsion systems in UAVs is to provide durable, reliable, and extended flight. Currently, no such engine for UAV applications are manufactured in India, and defence sector relies on imported engines only, which severely restricts their application for various other defence applications. This chapter addresses technical issues present in these systems, thus contributing to their development. Aspects related to structural and thermal analysis of engine components have also been discussed, which are essential for designing such engines. This chapter gives broad idea about future of UAV propulsion systems and associated challenges.

Keywords UAVs · Structural analysis · Thermal analysis · Defence · Small engines

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A. P. Singh et al. (eds.), *Advanced Combustion Techniques and Engine Technologies for the Automotive Sector*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-15-0368-9_11

11.1 Introduction

11.1.1 Background of UAVs

UAV has been known by a remotely piloted vehicle, a drone, a robot plane, or a pilotless aircraft. Public and media often use the term “drone” for this application. A UAV is defined as a powered, pilot-less aerial vehicle, which can transfer a lethal or non-lethal pay load. They can fly for long period at controlled speed and height and have many applications in defense, industrial and civilian sectors. They were initially developed for 3-D missions: “Dull, Dirty or Dangerous” for humans. A sophisticated UAV may cost up to tens of millions of US dollars, and their weight may range from ½ to 20,000 kg (Friedrich 2014).

UAVs have been used across the globe since last couple of centuries. The earliest reported use of a UAV was by Austrians, who destroyed the Italian city of Venice with unmanned explosive balloons in 1849. In 1930s, use of a drone as moving target shooting by aircrafts was an important application, in which a two-stroke gasoline engine was used to power these drones. Remote-controlled aircrafts gained popularity during this phase. These aircraft featured in model Aircraft Nationals Competition held in Detroit in 1937. Later, in 1980s, USA developed aircraft to meet growing demand of the market with the aim of cost optimization. In 1986, USA and Israel worked together to develop a new aircraft named as RQ2 Pioneer (Tsach et al. 2004; Kumar et al. 2015). In 2000, USA introduced drones for the search of Osama Bin Laden in Afghanistan. In 2014, Amazon planned to use drones for doorstep delivery to enhance customer service experience. There is a vast potential for research and development of UAVs and their expansion to numerous fields of life.

11.1.2 Potential Applications of UAVs

There are many sectors, where UAVs can be used, such as military, agriculture, civilian, healthcare, and many more. Below are some sectors for applications of UAVs:

11.1.2.1 Geomorphic Mapping

UAVs provide a low-cost and high-pixel aerial photography in different areas. Such photography is vital for mapping studies in earth sciences. Techniques like laser scanning and low-altitude aerial photography by light aircrafts may provide excellent spatial resolution, however they are expensive and time-consuming. There are strict restrictions for UAVs usage in many areas, however due to their application in a broad range of resolutions, popularity of UAVs in geomorphic studies has increased. Recent technological developments have seen UAVs act as a means, by which we can collect high-resolution aerial photos over large spatial areas. The flexibility and shorter response time of UAVs are the reason for increasing interest of geomorphological community (Hackney and Clayton 2015).

11.1.2.2 Pedestrian Traffic Monitoring

UAVs are used for collecting data, and controlling pedestrian traffic flows, in order to monitor the pedestrian demand. Present methods such as manual observers, video recording on site, questionnaire survey are less efficient and less accurate. Such practices have several limitations, when surveying a large area. UAV technology has been used in many foreign countries such as Thailand (Tsach et al. 2004), where UAVs collect data comprehensively to overcome space constraints. It is a safe and less costly technology to use. However, UAV have few limitations in terms of technical, working, and legal issues, therefore use of UAVs need legal permissions from aviation authorities, which makes its deployment challenging for various applications, including pedestrian traffic monitoring (Sutheerakul et al. 2017).

11.1.2.3 Agriculture

UAVs have been used in agriculture due to their ability to cover large areas quickly without damaging the growing field. They are quickly becoming popular in developing countries like India. They are widely used to achieve precision farming and smart agriculture in crop research and development. For monitoring small and medium sized areas in lesser time, UAVs can provide detailed information about the soil condition, crop, and soil moisture. Precision farming includes sensor data and real-time data analysis in order to improve farm productivity. Data collected from drones are used for soil health scans, in order to monitor crop health, and planning irrigation schedules. Upcoming agricultural revolution is predicted to be driven by data, which will help increase agricultural productivity with minimum damage to the environment and provide benefits to farming communities.

11.1.2.4 Aerospace and Military

The aerospace industry has been exploring the use of UAVs to provide increased accuracy and ease of documentation. These UAVs are capable of offering onboard image processing, and locking onto a target, apart from tracking it. UAVs are extensively used in military operations since last one decade for collecting information, surveillance, monitoring enemy activities, and to attack military targets and terrorist hideouts. Generally, they are preferred for a mission that is too dangerous for manned aircraft. Drones are a real-time tool for commanders to make better decision in resource allocation and to search for lost or injured soldiers. Military UAVs are classified based on the kind of operations they perform. Advantages such as lightweight, quieter operation, smaller size and high efficiency render them useful for defence applications.[1]

11.1.2.5 Civil Engineering

Most civil engineering inspections pose a risk to inspection staff, inconvenience to the public, and potential damages to the structures. Traditional inspection methodology requires significant human resources and equipment, resulting in increased costs. UAV's vertical and oblique photography can collect real-time data for site data analysis. UAVs add great value by safely navigating into hazardous and harsh terrains. Innovative and rapidly evolving drone technology would benefit civil engineers and surveyors enormously.[2]

11.1.2.6 Healthcare

Drones are used for surveillance of sites affected by biological and chemical disasters. One of the best application of drones for healthcare is to deliver emergency medication or equipment to remotely located patients. Flood, earthquakes, fire, and severe drought can prevent on-site interaction with medical persons. Drones could be helpful in an emergency, where no one might be available. They can deliver medical aids to refugees and victims of war or military conflict. In future, smaller drones would provide medicine to patients at home, leading to rapid care and reduction in cost of assisting people.

On the other hand, there are technical challenges such as improving the ability of drones to detect and avoid objects during flight, reducing their size and weight, and preventing hackers from misusing this technology. It is therefore required to accelerate research efforts related to safety, response time, and privacy-related issues. Other challenges for UAV systems include flexibility of refueling and overall efficiency compared to manned aircraft.

11.2 Prospects and Limitations of Various Propulsion Systems for UAVs

A propulsion system provides effort to the aircraft for traveling from one point to another. Hence propulsion system should be durable, controllable, and energy

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[1] https://www.isro.gov.in/applications-of-unmanned-aerial-vehicle-uav-based-remote-sensing-ne-region.

[2] http://www.asctec.de/en/uav-uas-drone-applications/uav-civil-engineering-buliding-stock-condition-survey/.

efficient. Failure of propulsion may lead to loss of aircraft control. Therefore an in-depth research study on pros and cons of different propulsion systems available in the market should be done before their implementation for UAV applications. In the following sections, few propulsion systems are listed, along with their advantages, disadvantages, and associated technical challenges.

Extended range and reliability of UAVs are two major constraints for the Wankel rotary engines, gas turbine engines and electric motor-based systems. Internal combustion (IC) engines are a potential solution to overcome some of these challenges. In the next section, reciprocating piston engines as a propulsion system for UAVs is discussed (Table 11.1).

11.3 IC Engine as UAV Propulsion System

Engines used in civil aviation and general aviation sectors are either gas turbines fuelled by aviation kerosene or IC engines fuelled by gasoline. These engines operate on the same principle as spark ignition (SI) engines used for automotive sector (Masiol and Harrison 2014). Reciprocating piston engines are classified based on the number of cylinders used (single-cylinder, two-cylinders and so on), the arrangement of cylinders (in-line, radial, opposed, V-configuration etc.) and working cycle (two-strokes and four-strokes). High power-to-weight ratio, compactness, low-cost, high efficiency, and reliability are the essential requirements for designing a piston engine for aviation sector and UAVs. Two stroke engines offer advantages such as high mechanical efficiency and high-power density. Supercharging of these engines may further improve power density and fuel efficiency at higher altitudes. The main issue with two-stroke engine is its poor scavenging process. Many researchers have given attention to scavenging models in order to optimize the design of port arrangement. Qiao et al. (2018) performed optimization of geometric parameters of the scavenging ports of a two-stroke small aero engine. This work provides necessary information about the design of crankcase scavenging system of aero engines. Visualization tool such as AVL FIRE software was used to study the gas composition and its distribution inside the combustion chamber during scavenging process. Borghi et al. (2017) investigated the design and modifications of a two-stroke single-cylinder engine. The primary step of this study involved fabrication of scavenging and combustion systems. The air metering system was modified for the constructed prototype during the second step. This modified engine was compared with the four-stroke engine developed for the same application. The only problem with the two-stroke engine was poor emission compliance of low NO_x limits, which can be possibly solved by using an efficient exhaust gas after-treatment device. Carlucci et al. (2016) simulated two-stroke engine by varying the design parameters such as modification of exhaust valves, scavenging ports (area of each port and number of ports), compression ratio, pressure ratio of both compressors (high and low) and air-fuel ratio (AFR). The objective was to increase the brake power output and to reduce the specific fuel consumption of the engine for having an economical flight.

Table 11.1 Types of propulsion system used in UAVs

S. No.	Propulsion system	Advantages	Disadvantages	Technical challenges
1.	Reciprocating piston engines (Griffis et al. 2009)	Light in weight, small in size, forced induction for high altitude application	Noisy, produce vibrations as it has many moving parts, lubrication and cooling required	Noise and vibrations affect reliability and life of the engine; seal failure may cause power loss, high temperature may lead to engine seizure or failure
2.	Wankel rotary engines	High power-to-weight ratio, compact, less noisy, less vibrations, lighter in weight, not prone to knock	Fuel consumption is more, not capable to meet emission norms, limited information available, complex	High exhaust gas temperature, engine cooling is difficult due to the intricate and complex design
3.	Gas turbine engines (Griffis et al. 2009)	High power density, tremendous thrust capability, insensitive to fuel quality	Expensive, loud, complex, less efficient than reciprocating engines at idle, high internal temperatures	Blade imbalance leads to vibrations, wear in bearing due to improper lubrication, high operating temperature, high energy rotation of the engine may damage the system
4.	Electric motor-based systems (Chan 2019)	Reliable and robust, high torque, less noisy, less maintenance required	Interference caused due to electromagnetic field, requires an enormous amount of current (Wu and Bucknall 2016). May be sensitive to water and other conductive liquids	Electromagnetic interference, corrosion, transients and noise produced by electromagnetic activity may obstruct the UAV electronics and communication devices, high current densities can corrode terminals

11.4 Design and Development of Engine for UAV Application

The constraints of time and range of UAV flight are the two main challenges, which need to be resolved for strengthening UAV applications. This study can be viewed as an attempt to resolve these problems to some extent. Engines are a viable alternative due to the advantages they offer such as high power output, greater refinement, and smoothness during the engine operation. Also, compact and small sized engine designs can enhance their usage in defence applications.

The methodology for design of UAV engines is summarised as follows: (Fig. 11.1).

- CAD model development of engine components,
- Structural and thermal analysis of the engine prototype,
- Manufacturing and testing of engine components for prototype development,
- Development of experimental setup for the prototype engine testing and experimental investigation for engine performance and durability characteristics,
- Powering the UAV using a compact engine and its functional flight testing.

IC engines have played a great role in human life, and researchers continuously seek to develop an engine with higher efficiency, low brake fuel consumption, and lower emissions from exhaust tailpipe. The transport industry uses IC engines to transfer people and goods from one place to another. If we look closely, an IC engine operates best when there is perfect synchronization between its components. Therefore, different IC engine component such as piston, piston rings, cylinder liners, valve assembly, connecting rod, crankshaft, camshaft, cylinder block, bearing cap, cylinder head, gear trains, etc. have to go through essential structural and thermal failure analysis to prevent any accident. These design aspects are discussed in the following sections.

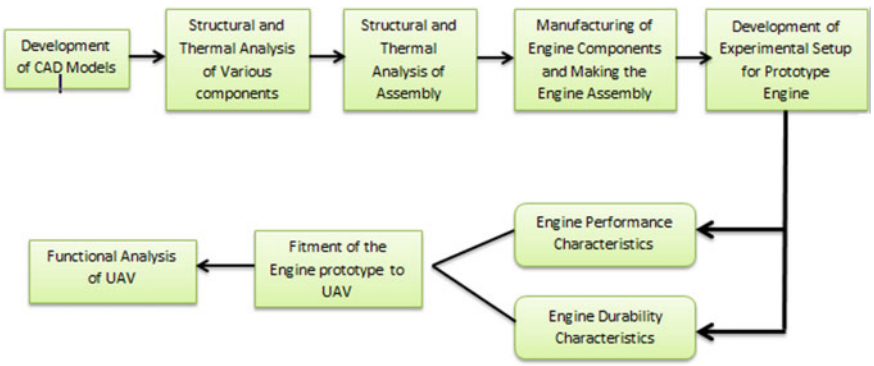

Fig. 11.1 Methodology for design and prototyping of UAV engine

11.4.1 Structural Analysis of Engine Components

Yu and Xu (2005) studied the crankshaft failure due to propagation of a fatigue crack in a stress concentration region. The crankshaft failed in a lesser than average life cycle. It was observed that surface hardening by nitriding could increase the fatigue strength of the material. Çevik and Gürbüz (2013) reported the effect of fillet rolling on the fatigue behavior of the crankshaft. The result showed that induced compressive residual stresses provide remarkable advancement in the fatigue strength of the component. Ktari et al. (2011) investigated the failure of three crankshafts made of forged carbon steel. Reasons for all failures was crack propagation and fatigue caused due to high stresses at fillet radius. Witek et al. (2017) performed numerical modeling of the crankshaft of a compression ignition (CI) engine using Finite Element Method (FEM). They reported that the main reason for early fatigue failure was the alternating bending stresses due to notch effect. Oil filters got clogged due to collection of metal debris in the lubrication channels, causing catastrophic engine failure, which further led to damage of other components such as piston, connecting rod, bearing, crankcase.

11.4.1.1 Piston

Piston is one of the most important components in the engine. Its function is to convert force from high pressure, high-temperature expanding gases to reciprocating motion, which is eventually converted to crankshaft rotation by crank-slider mechanism. Reciprocating motion of the piston leads to balancing issues in the engine, which cause vibrations. Friction between the cylinder wall and piston rings leads to components wear and degradation, hence reduces useful life of the engine. Noise generated by the engine can be unbearable sometimes. To diminish the loudness of engines, many reciprocating engines use heavy noise suppression devices. Figure 11.2 shows the induced stresses in the piston.

Generally, Aluminum alloys are used for manufacturing piston since it has excellent thermal conductivity and they are light in weight. Aluminum expands when the temperature increases, hence appropriate clearance should be given to provide free piston motion inside the cylinder bore under high temperature conditions. Insufficient clearance may lead to piston seizure in the cylinder, however excessive clearance may result in loss of compression and generate piston noise.

The piston includes the piston head, piston pin bore, piston pin, skirt, ring grooves, and piston rings. Piston head is the top surface of the piston, which bears immense pressure and heat during the engine operation. Piston pin bore is created to hold the piston pin, which connects the small end of the connecting rod to the piston. A portion of the piston closest to the crankshaft is called skirt, which aligns the piston during reciprocating motion in the cylinder bore. The secondary aim of the skirt profile is to reduce piston weight and to provide space for rotating crankshaft counter-weights (Siva Prasad et al. 2016).

Fig. 11.2 Induced stresses in typical piston (Hemasundaram and Suresh 2015)

11.4.1.2 Piston Rings

A ring grooves are provided on the outer diameter of the piston and are used to hold different piston rings (Fig. 11.3). A piston ring is a dynamic seal, which prevents leakage of high-temperature gases from the pressurized combustion chamber. Piston rings are subjected to wear since they move in the cylinder bore. They get worn out in preference to cylinder walls, in order to prevent frequent replacement cylinder liner. Piston rings are generally made of cast iron, which provides good wear resistance. Piston rings also transfer heat from the piston to the cylinder walls and also scrap the excess lubricating oil back to the engine crankcase. Piston ring configuration and number of rings used in an engine depends on the engine capacity and material of the cylinder liner (Satyanarayana and Renuka 2016).

Piston rings used commonly include compression rings, wiper ring, and oil ring. A compression ring is located in the ring groove closest to the piston head, in order to prevent any gas leakage during combustion. Wiper ring is inserted in between

Fig. 11.3 Typical piston rings (Hemasundaram and Suresh 2015)

Fig. 11.4 Camshaft (Hemasundaram and Suresh 2015)

the compression and the oil ring. Its function is to seal the combustion gases further and wipe excess oil from the cylinder wall. Oil ring is generally located near the crankcase, and it mainly transfers excess lubricating oil to the oil reservoir during piston motion.

11.4.1.3 Camshaft

Camshaft (Fig. 11.4) function is to open and close inlet and exhaust valves in sync with the motion of piston. Main part of camshaft is lobes. Camshaft is forged from a single piece of steel. There are twice as many lobes as the number of cylinders plus one additional lobe for the fuel pump actuation (Swamulu et al. 2015; Naga Manendhar Rao et al. 2017). Crankshaft powers the camshaft. Rotational speed of the camshaft is always half that of crankshaft. For a four-stroke engine cycle, camshaft rotates by 180° for every 360° rotation of the crankshaft.

The most common configurations of the overhead camshafts are:

I. Single Over Head Cam (SOHC): In this configuration, a single camshaft is used to actuate all valves of the engine—Inlet valves and exhaust valves.
II. Dual/Double Over Head Cam (DOHC): In this configuration, two separate camshafts are used to operate the intake and exhaust valves, respectively.
III. Over Head Valve (OHV): This particular configuration is suited for V engine configuration. In this arrangement, a single camshaft is mounted between the two banks of cylinders. The cam lobes actuate the intake and exhaust valves through pushrods.

11.4.1.4 Crankshaft

The function of crankshaft is to convert the reciprocating motion of the piston into rotary motion and vice versa. Crankshaft is connected to a flywheel in order to damp pulsations in the cycle. Flywheel acts as an energy reservoir, which stores excess energy from the piston generated during the power stroke and uses the same energy for piston movement during remaining three strokes due to its high inertia. The

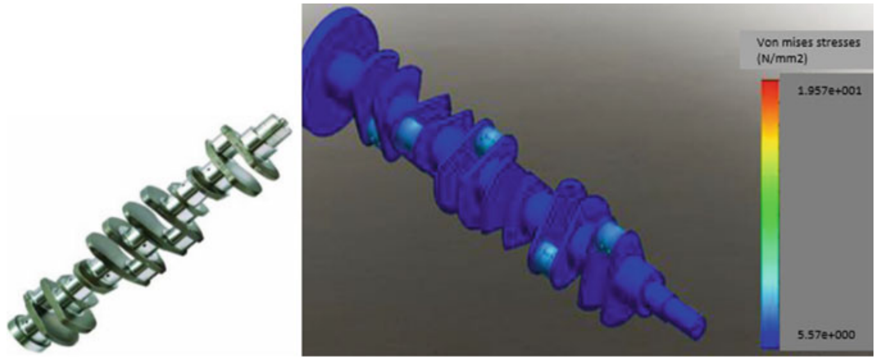

Fig. 11.5 Induced stresses in a typical crankshaft (Hemasundaram and Suresh 2015)

crankshaft is connected to camshaft via a belt-drive, which controls the opening and closing of inlet and exhaust valves. Crankshaft should be carefully designed for its weights and balances in order to reduce engine vibrations. Both ends of crankshaft are fixed on the engine block by using crank bearings. Balancing of crankshaft is vital for perfect functioning of the engine. Material selection and weight distribution on the sides of the journal should be done carefully. Failure analysis of crankshaft using ANSYS software helps predict critical design points in the model for UAV application. Figure 11.5 shows the crankshaft and its variation of induced stresses. Generally, heavy cast iron is used for manufacturing crankshaft for automotive applications and stainless steel for high-performance UAV engines (Reddy et al. 2017).

11.4.1.5 Connecting Rod

Connecting rod links the piston to the crankshaft, and its function is to transfer forces from the piston to the crankshaft, which further passes it on to the transmission (Kushwaha and Parkhe 2018).

Connecting rod is often a major source of catastrophic engine failure; therefore it requires care to ensure that it does not fail. Figure 11.6 shows the variations of induced stresses in a typical connecting rod. The traditional connecting rod used in the automotive industry is forged, and is suitable for lower horsepower engines (Singh et al. 2017). The materials used for manufacturing the connecting rods are steel alloy, aluminium, and titanium, depending on application requirements. A lightweight connecting rod is preferred for improved efficiency of the engines for UAV applications. However this goal should not be achieved by removal of material or changing design parameters but by using lightweight stronger materials.

Fig. 11.6 Induced stresses in typical connecting rod (Hemasundaram and Suresh 2015)

11.4.2 Thermal Analysis of Engine Components

Thermal failure is a bottleneck for engine development, which affected engine performance and efficiency. Engine heat transfer phenomenon is still not well understood by designers due to complex geometry and lack of understanding of combustion phenomenon. Therefore, it is necessary to study temperature distributions in the engine components for controlling thermal stresses and strains within acceptable limits and avoid component deformation. Thermal analysis allows researcher to design components and understand their temperature distribution even before the construction of the first prototype (Li 1982). It saves time and is a cost-effective way to optimize component design. Many researchers have reported critical design considerations for thermal expansion, which ultimately lead to catastrophic failure of engine components.

Abbes et al. (2004) studied the behavior of a direct injection compression ignition (DICI) engine piston, which was subjected to both thermal and mechanical stresses. Results obtained from the simulation were used to analyze the working temperatures. In another study, Esfahanian et al. (2006) studied three combustion boundary conditions and investigated heat transfer through the piston using KIVA and NASTRAN codes. Lu et al. (2013) used an inverse heat transfer method to study thermal analysis of a marine CI engine piston. New design showed improved performance from piston thermal loading analysis perspective.

Yao and Qian (2018) carried out research involving improvement in engine performance when nano-ceramic coating was applied over aluminum piston. Steady-state thermal analyses were used to determine the effects of ceramic coating on piston temperature distributions. By using FEM analysis, comparison between coated and uncoated pistons were made, as shown in Fig. 11.7. They showed that the temperature of the coated piston crown was higher than the uncoated piston, which improved the thermal efficiency and reduced the emissions.

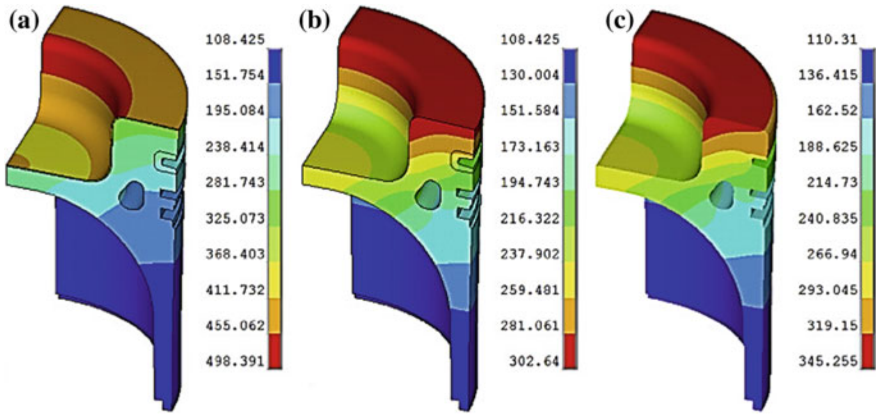

Fig. 11.7 Temperature distribution of the **a** thermal barrier coating (TBCs) piston, **b** aluminum alloy substrate of the TBC piston, and **c** conventional aluminum alloy piston (Yao and Qian 2018)

Satyanarayana et al. (2018) conducted quasi dynamic stress analysis for different compression ratios of a diesel engine. Figure 11.8 shows the variations in temperature, Von-mises stress, total heat flux, factor of safety (FOS), total deformation, and elastic

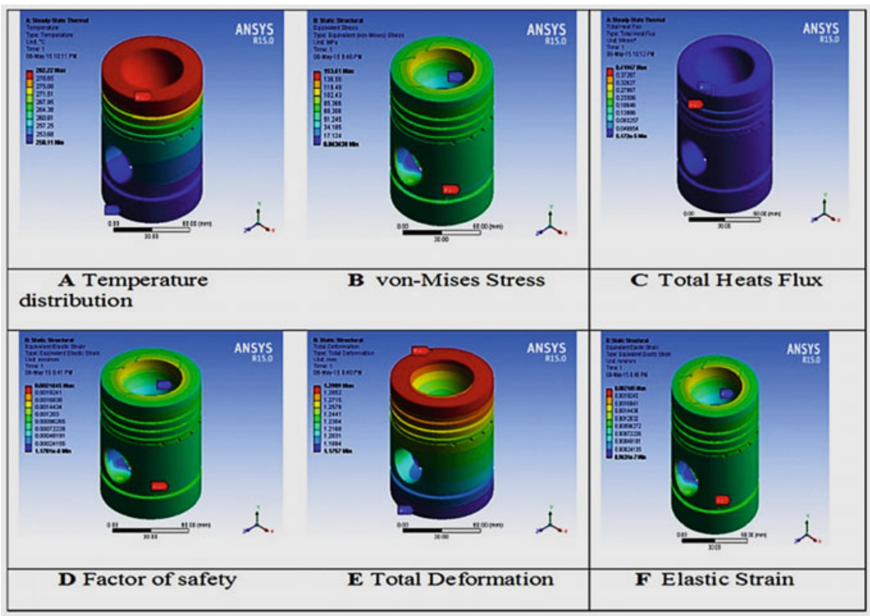

Fig. 11.8 Structural and thermal analysis of piston for a compression ratio of 16.5 (Satyanarayana et al. 2018)

strain on the piston. The maximum and minimum temperatures were observed at the piston crown and skirt respectively at all compression ratios. They reported that the compression ratio had a profound effect on the stresses developed.

11.5 Challenges of Research in UAV Propulsion Systems

Air pollution is a major concern for developing countries like India due to rapid expansion of transport and civil aviation sectors. Most studies highlighted that aviation emissions affect local as well as global air quality adversely. Emission standards for new aviation engines are enforced by the International Civil Aviation Organization (ICAO).

Design and optimization of small IC engines to achieve maximum efficiency includes modifications in various components of the engine. The intake port is one of the most vital part of the IC engine, which supplies air to the engine cylinder. It influences the quantity of air entering into the cylinder, velocity distribution, and in-cylinder air-flow characteristics. Therefore design of intake port becomes critical to reduce emissions and fuel consumption. For the optimization of in-cylinder air-flow characteristics, study of flow-field can be done by using advanced optical diagnostic techniques such as Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV). Computational Fluid Dynamics (CFD) analysis can help detect problems in the engine design.

Wang et al. (2019) proposed an AFR controlled fuel supply system to optimize the efficiency of UAV, when operating at required engine speed. The results showed 9–33% improvement in engine efficiency. Hassantabar et al. (2019) studied the electronic fuel injection system since carburetor was not suitable for two-stroke UAV engine. They investigated the airflow and fuel spray structure in the throttle body injection system using CFD tools. Simulation of two-stroke engine was performed using 'Lotus' engine. They also developed models to compute the performance of the system in different working conditions, which showed the effect of engine speed on the pressure drop, spray characteristics, and turbulence patterns.

Light weighing of the engine is an effective way to achieve small and compact UAVs. It involves use of lightweight material and advanced manufacturing processes to deliver enhanced technical performance. This concept is widely explored in automotive industry as well. Aluminium alloys have been used as major material used in aerospace industry. Nayak and Date (2018) redesigned the UAV engine piston using sheet metal manufacturing process consisting of deep drawing, redrawing, ironing, punching, and hole flanging. Die and punch of forming process were developed and implemented successfully. A 24% reduction in weight was achieved compared to the existing piston. Decisions like whether to use one or multiple propulsion for specific flight segment creates a new dimension of research for researchers. Opportunities do exist, however they also bring challenges such as engine design modifications to optimize engine design parameters for UAV engines. we need to explore novel approaches to improve overall efficiency and flow simulation techniques to meet emission norms for these UAV engines.

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