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Testing Composite Valve Covers for Reciprocating Engine Applications

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Abstract: The use of composites within the aeronautical field is not limited to airframe applications and includes powerplant components in reciprocating engines. To add to the research body in this area, the presented work aimed to evaluate the performance of novel carbon fiber valve covers installed on an aircraft reciprocating engine. Specifically, the comparative performance between novel composite-based valve covers and original steel valve covers was of interest, with a focus on the thermal and cooling behavior. The experimental procedure simulated certification testing required for parts manufacturer approval provided by the Federal Aviation Administration and followed the cooling test protocol outlined by ASTM International. The test engine was run once with each valve cover type and at multiple power settings, throughout which the surface temperature of the valve covers was recorded. In addition, the carbon fiber valve cover was subjected to a post-run visual inspection to identify the overall condition thereof and any potential damage introduced under engine operating conditions. The experimental study revealed lower temperatures with accompanying higher cooling and heating rates for the carbon fiber valve cover when compared to the original steel valve cover. Moreover, sealing issues on the carbon fiber valve cover were observed. The high heating rates coupled with the sealing issues can have a detrimental impact on the engine operation and lifetime, thus, equivalency requirements were not met. While the novel carbon fiber valve cover did not perform at directly equivalent levels to the original steel valve cover, the potential for future improved performance is demonstrated. Especially the lower temperatures sustained, the rapid cooling rate, and the weight savings associated with the use of composite materials are promising. Moreover, the results obtained can be used to further refine the design of composite-based valve covers, with the ultimate goal of meeting certification and applicational requirements.

Keywords: Composites, Carbon Fiber, Reciprocating Engines, FAA Certification, Testing

Introduction

The use of composite materials in the aeronautical and aerospace industry has drastically increased over the last decades, with their use expanding in more recent years to primary, load-carrying structures (Hiken, 2017; Kassapoglou, 2013; Mouritz, 2012). Common applications of composite materials in the aeronautical field include control surfaces, stabilizers, floor beams, wings, wing boxes, pressure bulkheads, and fuselages (Hiken, 2017; Kassapoglou, 2013). However, the use of composite materials is not solely limited to airframe applications but has also expanded to powerplant components. For instance, gas turbine engine fan blades, containment cases, as well as cowlings and nacelles rely on composite materials due to their structural strength, reduced weight, sound absorption capabilities, and ease of manufacturing for complex shapes (Anoshkin *et al.*, 2018; Corman *et al.*, 2016; Ma *et al.*, 2017; Marsh, 2012). The attractiveness of fiber-reinforced composite materials has similarly been an incentive for the development of composite-based parts for reciprocating, internal combustion engines (Beckmann and Oetting, 1985; Buckley *et al.*, 2005). Common engine parts that have been of interest in terms of composite manufacturability and viability include valve train components, pistons, connecting rods, crankshafts, camshafts, and push rods (Buckley *et al.*, 2005; Kumaraswamy *et al*., 2021). Nevertheless, with few exceptions, the research efforts in this area have mostly been focused on automotive applications. Relating to aeronautical applications, Trunzo *et al*. (2012) manufactured and tested connecting rods and crankcases made of a combination of carbon fiber and aluminum on a reciprocating engine for Unmanned Aerial Vehicle (UAV) applications. Similarly, even though a non-internal part, Wang *et al*. (2014) manufactured carbon fiber valve covers for an aircraft reciprocating engine.

In this study, the carbon fiber valve covers manufactured by Wang *et al.* (2014) were tested under simulated flight conditions. Specifically, testing requirements for Federal Aviation Administration (FAA) certification were followed to evaluate whether the novel valve covers perform at the same level as traditional, steel valve covers, and thus, would qualify for the corresponding certification and aircraft application. The operational test is intended to serve as an initial survey, proof-of-concept style study, to characterize the temperatures and environmental conditions the carbon fiber valve covers are exposed to, and to identify potential damage sustained thereby. Furthermore, the valve cover manufacturing methodology presented by Wang *et al*. (2014) includes modern techniques such as reverse engineering and 3D printing of the composite mold. Therefore, evaluating the final product manufactured through said methods (i.e., the tested carbon fiber valve covers) will, by extension, serve as an assessment of the viability and performance of the 21st-century manufacturing methods used by Wang *et al*. (2014).

Certification and Testing Requirements of Aircraft Parts and Products

In the United States, as regulated by the Federal Aviation Administration (FAA), parts to be installed on aircraft are to be properly and adequately approved and certified. Part 21 of Title 14 of the Code of Federal Regulations (CFR) controls the certification of products and articles while outlining the requirements to obtain said approvals (FAA, 2009). Relating to the certification of aircraft parts/articles, two main paths for approval exist (1) Parts Manufacturer Approval (PMA) and (2) Technical Standard Orders (TSO) (FAA, 2009). Through PMA approval, manufacturers can produce certified (replacement and modified) parts that can be installed on applicable aircraft (FAA, 2009). In this study, thus, PMA procedures were considered given that the manufactured valve covers are conceptualized as potential replacement parts.

The most essential requirement of a PMA is that the part of interest has to meet the airworthiness requirements set forth by the FAA (2009). As such, a critical component to obtaining a PMA consists of performing a range of tests that allow validating that the part under consideration meets the required and applicable airworthiness requirements (FAA, 2014). These airworthiness requirements are regulated under a range of Parts under Title 14 CFR and are dependent on the exact category of aircraft that the part, article, or product is to be installed on (FAA, n.d.). In the paragraph below, the specific requirements for reciprocating engines are discussed.

Two general forms of testing can be performed to prove that the airworthiness requirements are met: (1) comparative testing and (2) general testing (FAA, 2014). Comparative testing refers to testing both, the new part to be certified and the original certified part to be replaced (with zero time), and comparing the results to indicate equivalent – or improved – performance. General testing, on the other hand, includes only testing the new part to be certified, while using the results of these tests to highlight how the certification requirements are met (FAA, 2014). The FAA (n.d., 2014) provides further details on both types of tests as well as the specific airworthiness requirements. It is important to highlight, moreover, that in the presented work and experimental study the PMA requirements were merely followed as a guideline to establish a basis for the exploratory, proof-of-concept type test performed.

The testing requirements for the certification of reciprocating engines outlined by the FAA are dictated under Title 14 CFR Part 33, Subpart D (FAA, 1964). Specifically, the outlined procedures include tests for vibration, calibration tests, detonation tests, endurance tests, operation tests, tests of the engine components and the engine as a system, as well as a complete teardown inspection to evaluate the state of the engine and parts post-testing. While the FAA does not outline specific testing standards or practices to be used for the certification testing of reciprocating engines, advisory circular (AC) 33.91-1 (FAA, 2010) guides similar tests for turbine engines.

General tests applicable to both, turbine and reciprocating aircraft engines can also be used as references to evaluate the performance of engine components. Referencing specifically reciprocating engines, ASTM Standard F3064/F3064M-21 (ASTM International, 2021) outlines requirements and tests for the installation of powerplants, the operation of controls, instrumentation, sensors, and indicators, as well as the operational characteristics thereof. Similarly, the unique characteristics presented by aircraft composite materials are also to be considered during testing. For this purpose, SAE International Standard AERP 6287 (2018) provides testing methods to characterize the environmental exposures that composite materials may be subjected to throughout their operational lifetime.

Thermal Testing of Aircraft Engine Components

The overall performance of an engine can be monitored through a series of parameters (Miljković, 2013). Specifically, temperature parameters have been carefully considered in studies that focused on evaluating the performance and characteristics of reciprocating engines and associated components when design changes or novel technologies were implemented (Czarnigowski *et al*., 2019; Woś and Michalski, 2011). Additionally, the temperature and the number of thermal cycles to which engine components are exposed critically impact the durability, wear, stress, and Time Between Overhaul (TBO) thereof (Piancastelli *et al.,* 2012). By extension, temperature readings can be used as signals to monitor for underlying issues or malfunctions of reciprocating engines (Miljković, 2013).

Kumaraswamy *et al.* (2021) studied the thermal characteristics of hybrid metal matrix-based exhaust valves for automotive use, highlighting the importance of considering thermal properties when novel materials are investigated for engine applications. For aircraft reciprocating engines, however, limited studies have focused on thermal analyses of novel engine parts. One example includes a study by Chockalingam (2015), where the use of ceramic pistons in reciprocating engines was evaluated and a thermal analysis was performed to determine the operational characteristics thereof. Mohammed *et al.* (2018), similarly, analyzed the performance of fiber metal laminate composites in high-temperature environments (i.e., aircraft engines). While not for aircraft applications, Kass and Noakes (2017) considered the operational characteristics of a reciprocating engine containing parts manufactured via additive manufacturing. The evaluation thereof, nevertheless, was primarily focused on the pressure-based readings. Similarly, Hauser *et al*. (2006) and Trunzo *et al*. (2012) studied the use of novel materials for the manufacture of reciprocating engine parts, but testing and characterization efforts mainly focused on fatigue and strength aspects.

Study Aim and Contributions

In addition to the novelty presented by the manufacturing methods introduced by Wang *et al.* (2014) previously described, the performed study aimed to provide further original contributions. Specifically, these stem from basing the experimental method on FAA-mandated certification requirements. Through this approach, the testing that composite-based components would be subjected to before being certified for aircraft applications is simulated. Additionally, given the comparative nature of the study, the performance of the traditional steel valve covers and the novel carbon fiber valve covers could be directly compared. This, in turn, is further beneficial when considering the PMA certification framework delineated previously. Lastly, the study did not only consider operational aspects such as the sustained temperatures, but also focused on the condition of the novel composite valve covers after the operation. Through this, elements related to the design of the composite valve covers could also be assessed.

Materials and Methods

In the presented study, a comparative testing paradigm (as outlined by the FAA (2014) and previously introduced) was employed. In other words, the operation of the novel, carbon fiber valve covers were compared to the operation of the original, steel valve covers. Of the tests outlined by the FAA (1964), elements of the systems and component tests (FAA, 2008) and the teardown inspection (FAA, 1980) were selected. Specifically, the thermal characteristics of the valve covers were compared via a comparative simulated cooling test. Through this test, the maximum temperatures experienced by each respective valve cover as well as the respective heating and cooling rates were evaluated. ASTM International (2021) protocols were followed, and the normal operation of the engine in-flight was simulated to replicate the conditions, especially the temperatures, engine components and parts experience during all flight phases.

Engine Details

The engine used for the test was a Lycoming IO-320-B1A model: A four-cylinder, opposed, fuel-injected, direct drive engine type certified in 1963, shown in Fig. 1. The engine was installed on a Piper PA-30 Twin Comanche airframe before being repurposed as a test stand for educational purposes.

Carbon Fiber Valve Cover Fabrication

The process used to manufacture the novel carbon fiber valve covers evaluated is outlined by Wang *et al*. (2014). The manufacturing process employed a range of up-and-coming engineering tools, including reverse engineering, 3D printing, and composite-made compression molds. To ensure appropriate dimensional replication, the original steel valve covers were scanned via a 3D FARO scanner. The scanned result was finalized using CATIA software, and the generated surface was used as the basis for the compression mold required to fabricate the carbon fiber valve covers. The compression mold (shown in Fig. 2) was 3D printed using a composite printing filament based on 50% carbon fiber by weight (Wang *et al*., 2014). The composite layup consisted of four prepreg carbon fiber plies, while the flange area was reinforced with two further plies. The layup was cured in a heated press at 250°C for five hours, under three tons of pressure. The valve covers were finalized via sanding. In total, six carbon fiber valve covers were manufactured. However, the quality of the valve covers was found to be dependent on the condition of the 3D printed mold, which deteriorated with further uses (Wang *et al*., 2014). Therefore, the first valve cover manufactured using this process (as shown in Fig. 3) was used for the engine run. Figure 4 shows the final installation of the carbon fiber valve cover on the test engine.

Fig. 1: Lycoming IO-320-B1A test engine used

Fig. 2: 3D printed, carbon fiber/PPS compression mold Wang *et al*. (2014)

Fig. 3: Carbon fiber valve cover selected for testing

Engine Run

A flight test was simulated by performing an engine run (with the engine previously described and shown in Fig. 1) on the ground. Specifically, the guidelines provided by ASTM International (2021) were used as the basis for the flight test simulation. Per ASTM International (2021), the critical stages for cooling tests include the climb and descent stages of flight. It is important to note, however, that the standard refers to an actual flight test, while in the present study the flight conditions were replicated on the ground.

In total, two engine runs were performed – In the first run, the original, steel valve cover was installed on cylinder number four, while the novel carbon fiber valve cover was installed in the same cylinder during the second run. Cylinder four was selected as it is the hottest cylinder on the engine due to its inherent positioning in the second row, thus receiving less cooling air from the propeller and experiencing the highest temperatures. By using cylinder four, the performance of the valve covers at the most extreme temperature location could be evaluated. The engine was allowed to return to room temperature between both runs.

The outside surface temperature of the valve covers was measured and recorded in degrees Celsius (°C) at five-second intervals (i.e., every five seconds the surface temperature of the valve covers was appraised) via a Lascar Electronics EL-USB-TC K-type thermocouple (see Fig. 5). The five-second interval was chosen as it allowed for a good balance between collecting data at small enough intervals to note temperature changes in comparatively short periods, while at the same time reducing the amount of noise or clutter that is associated with measurements at smaller periods. The thermocouple was installed on the outside surface of each valve cover tested, as shown in Fig. 6.

The procedures, limits, and flight conditions for the engine run, as shown in Table 1, were adapted from the Airplane Flight Manual (AFM) (Killough, 1996), the engine's Type Certificate Data Sheet (TCDS) (FAA, 2018), and the Lycoming operator's manual (2006). The run time with each valve cover was approximately 20 min. However, the exact duration of each run varied slightly. Certain run phases did not have a fixed time requirement given that the specific settings were to be maintained until the engine stabilized or the test in question was completed (Killough, 1996; Lycoming, 2006). Similarly, in each run, the acceleration time to the specified power setting (i.e., Revolutions Per Minute, RPM) was different, affecting the run time. In Table 1, these phases are indicated by the duration being marked as a "variable". The exact duration of each engine run is provided in the "Results" section.

The engine run time provides the period over which the temperature of each valve cover is measured, recorded, and evaluated. It is important to add, nevertheless, that the temperature reading was not stopped until a certain period past the engine shut down. During the engine run, the backwash created from the rotating propeller provided additional cooling. The highest temperature reading, therefore, was expected after the engine run, when the propeller stopped providing cooling air motion. The details of this cooldown period-including the duration thereof-are provided under the "Results" section.

Post-Run Visual Inspection

Following the test run, the carbon fiber valve cover was subjected to a scaled-down visual inspection, per the FAA (1980). The purpose of the post-run inspection was to assess the overall state of the valve cover, as well as to identify any high-level damage that may have been introduced due to the exposure to high temperatures and other environmental factors. An initial visual inspection was performed while the valve cover was still installed on the engine. A second inspection was performed once the valve cover was uninstalled and cleaned.

Limitations to the Methodology

The results obtained are to be considered under the limitations imposed on the study. First, ASTM International (2021) provides additional testing requirements when the engine is to be installed on a multiengine aircraft (as is the case with the engine used in the study). Specifically, the loads experienced in a one-engine-inoperative situation during descent also would need to be simulated. However, this flight situation was not further explored as the test performed served as an initial survey to note differences in thermal exposure between the original steel valve covers and the new carbon fiber valve covers. Additionally, the basis of the evaluation performed was comparative testing. For this test, the original part that is being used as the reference point has to be at zero time (FAA, 2014). Nevertheless, the steel valve cover employed in this test was not a zero-time component.

Furthermore, variability was introduced into the results as the two valve cover types were tested in two separate engine runs. Therefore, slightly differing and changing environmental conditions may have influenced the results. Similarly, each separate engine run may inherently have slightly different operating characteristics, which could have added variation to the temperatures each valve cover was exposed to. The engine operation can further be impacted by the rest times between, and before, each run. The run with the steel valve cover was the first engine run on the test day, while the carbon fiber valve cover was featured on the second run of the day. The environmental and engine-specific differences introduced into the test were minimized and controlled through the experimental design. The engine was allowed to rest and cool down to room temperature between the two runs, in order to return the engine to the same initial conditions as before the first run. Second, both valve covers were installed on the same cylinder to eliminate potential cylinder-to-cylinder variation, especially in terms of cooling.

Lastly, as shown in Fig. 6 above, the thermocouple was installed on the outside of the valve covers. Nevertheless, the inside and the outside of the valve cover may be exposed to different temperatures, notably due to the propeller backwash effect on the outside of the covers. Subsequently, the potential for the temperature on the inside of the carbon fiber valve cover to be higher than the temperature recorded on the outside surface is to be considered.

Table 1: Engine run details

Phase	RPM	Duration
Run up	1200	4 min
Magneto drop test	1800	Variable
Before takeoff	1200	Variable
Take off and climb	2700	1.5 min
Cruise	2450	5 min
Descent	1200	5 min
Approach/landing	2400	1 min
Engine shut down-I	1200	Variable
Engine shut down-II	1800	15 sec
Engine shut down-III	1200	Variable

Fig. 4: Carbon fiber valve cover installation on the engine

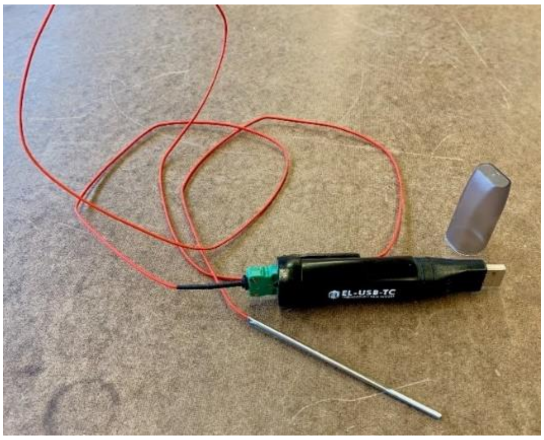

Fig. 5: EL-USB-TC thermocouple used for temperature measurements

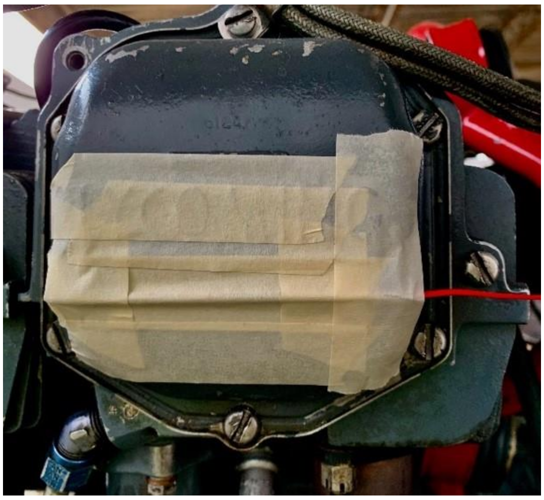

Fig. 6: Thermocouple installation for valve cover testing

Results

Both engine runs were performed on the same day, with a cool-down period of slightly above two hours separating each respective run. The environmental conditions for the two runs were as follows: 23°C, 94% relative humidity, and 24°C, 88% relative humidity for the first and second run, respectively. The first run lasted 23:02 min, while the duration of the second run was 21:40 min. The temperature recordings were not interrupted until after the peak temperature post-engine shut-down was recorded. For the engine run with the steel valve cover, the peak temperature was achieved 58 sec after the engine rotation stopped. The peak temperature for the run with the carbon fiber valve cover was measured at 2:35 min past the engine stop time.

Thermal Analysis

Figure 7 provides a visual representation of the valve cover surface temperature evolution along the engine run time. In other words, the graph in Fig. 7 highlights the temperature measured for each valve cover throughout each respective engine run. The graph includes 25 min of temperature data, reflecting the temperatures of the valve covers during the run and the time to reach peak temperatures after each run. Consequently, Fig. 7 allows to assess trends in, and the progression of, the temperatures each valve cover experienced. The takeaways from Fig. 7 are described throughout the subsequent paragraphs. It is important to note, however, that the horizontal axis does not represent the same stages of the engine run for each valve cover. As above mentioned, the time for each run varied. Therefore, the horizontal axis merely provides a time reference and does not indicate the engine run stages and RPMs.

A similar overarching pattern in temperature evolution can be recognized in Fig. 7 for both valve cover types. As the engine is started, the temperature progressively increased, ultimately leveling off – or showing a lower rate of temperature increase – between approximately run min 11 and 21 (refer to the horizontal axis of Fig. 7 for the minutes). Once the engine run was terminated and the propeller stopped rotating and providing backwash, the temperature of both valve cover types experienced a sharp, sudden increase. Nevertheless, the respective temperature curves display noticeable differences. With few exceptions that may be a result of the shifted horizontal axes, the steel valve cover (represented by the green trendline in Fig. 7) experienced higher temperatures through the run. The same trend is recognized in the temperature jump post-run, where the steel cover experienced a greater peak temperature than the carbon fiber valve cover. Moreover, the steel valve cover appears to be subject to fewer and less extreme temperature fluctuations during the run. Specifically, the carbon fiber valve cover (represented by the orange trendline in Fig. 7) experienced drastic temperature jumps – and subsequent fast cooling periods–approximately around run minutes seven, 13, and 18 (refer to the horizontal axis of Fig. 7 for the minutes). Even though the steel valve cover is also subject to temperature fluctuations through the run, these are not as prevalent and rampant as the ones measured on the carbon fiber valve covers.

Lastly, the increase in temperature observed post-run-approximately after min 21 for the carbon fiber valve cover and approximately after min 23 for the steel valve cover, as shown in Fig. 7 – presents a different behavior for each valve cover type. For the steel valve cover, the temperature rises comparatively quickly, reflected by the steep peak seen in Fig. 7, and the maximum temperature is achieved 58 seconds after the engine is shut-down. The behavior of the carbon fiber valve cover differs in two aspects. In addition to the temperature maximum for the carbon fiber valve being lower, the rate of heating is similarly lower than the heating rate of the steel valve cover. This can also be visually observed in Fig. 7. Therefore, the time elapsed (2:35 min) between the engine shut-down point and the peak temperature point of the carbon fiber valve cover is greater.

The temperature-related trends shown in Fig. 7 are further summarized in Table 2. The temperature of the steel valve cover was – on average – 7.09°C greater than the temperature of the carbon fiber valve cover during the run, excluding the post-run period, and 6.17°C greater when the post-run period is considered. An approximately similar difference between the valve cover types was observed for both temperature peaks: In-run with propeller backwash (9.5°C) as well as post-run, without propeller backwash (7°C). The carbon fiber valve cover had higher rates of heating and cooling during the run – with backwash – with the cooling rate showing the most drastic difference. Both, the heating and cooling rates with backwash were calculated with a time difference (Δ) of 1.5 min, as it represents the time interval used for the highest power setting operation. The post-run heating rate was calculated based on the time required for each valve cover to achieve the respective peak temperatures. Without backwash, the steel valve cover experienced a higher heating rate than the carbon fiber valve cover - contradicting the results obtained from run data and indicating a potential impact of the backwash on heating and cooling rates.

Post-Run Visual Inspection

Once the run with the carbon fiber valve cover was completed, the installation of the valve cover on cylinder four was inspected. During the inspection, no outside damage or any form of deterioration was noted. However, as shown in Fig. 8, oil was found flowing along the valve cover flange and pooling around the screw at the six o'clock position, indicating a potential sealing issue. However, no damage to the interior carbon fiber surface was found. Merely an oil film, shown in Fig. 9, to be expected from normal internal lubrication, was observed.

Table 2: Summary of valve cover temperature parameters

Parameter	Steel valve cover	Carbon fiber valve cover
Maximum temperature-post-run	73.5°C	66.5°C
Maximum temperature-backwash	58.5°C	49°C
Average temperature-backwash	49.19°C	42.10°C
Average temperature-w/post-run	49.815°C	43.65°C
Maximum heating rate-backwash	3.67°C/min	4.33°C/min
Maximum cooling rate-backwash	-1.67°C/min	-4.33°C/min
Heating rate-post-run	18.54°C/min	8.90°C/min

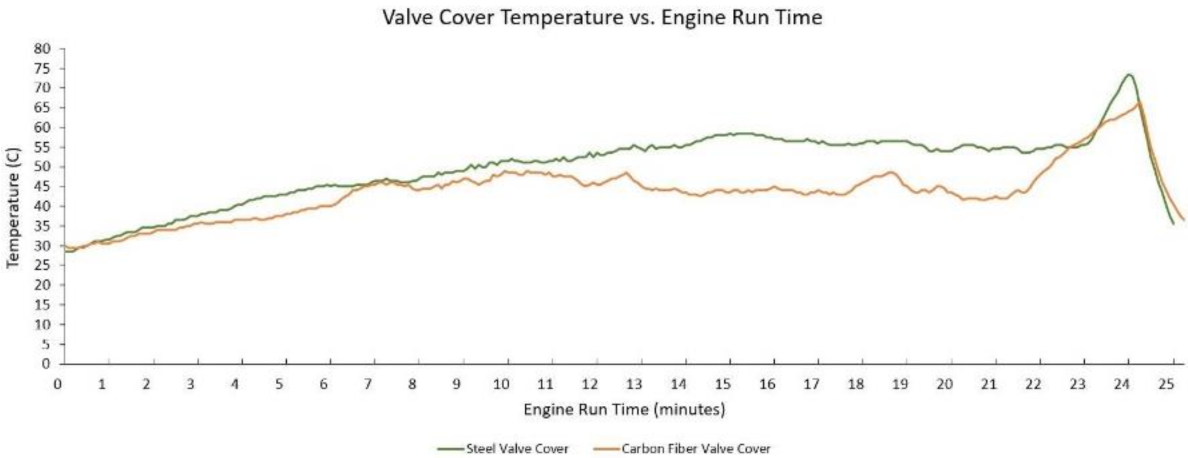

Fig. 7: Valve cover temperature evolution with a run time

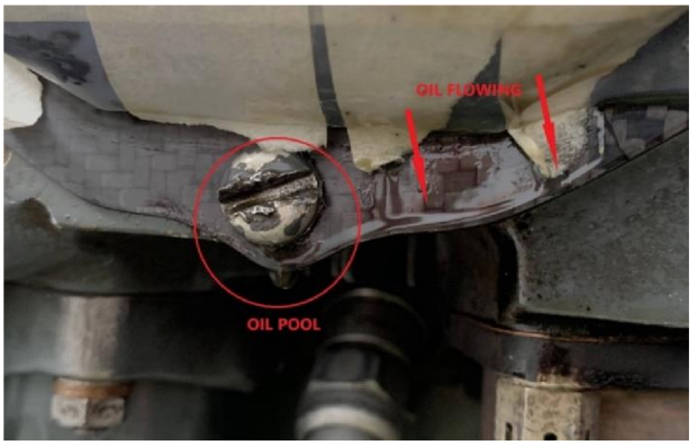

Fig. 8: Oil pool on carbon fiber valve cover

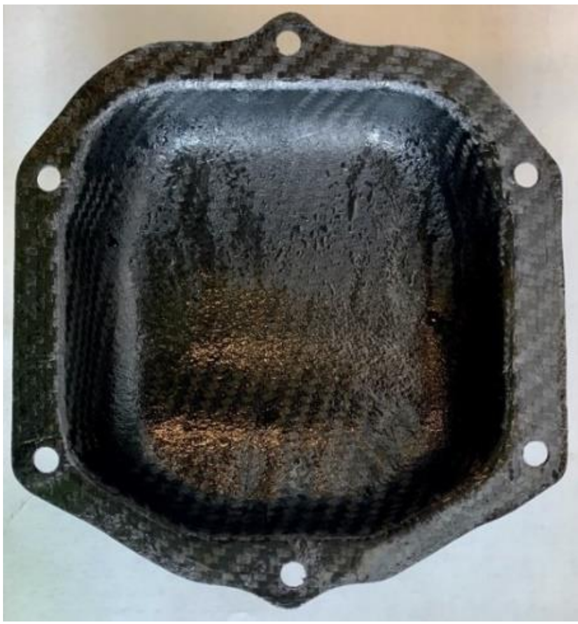

Fig. 9: Internal surface of the carbon fiber valve cover post-run

Discussion

The main objective of the study was to evaluate whether the valve covers manufactured as described per Wang *et al.* (2014) match – or surpass – the performance of the traditionally used steel valve covers, and, subsequently, would be able to obtain an FAA PMA. Specifically, two elements of the PMA testing requirements were considered: Thermal performance and overall condition. The first was evaluated by comparing sustained temperatures during the simulated engine run - as outlined per ASTM International (2021) - while the latter was assessed via a post-run visual inspection.

The novel carbon fiber valve cover sustained lower temperatures and presented higher heating and cooling rates while exposed to the propeller backwash. These conditions, especially when considered in the long run, can be beneficial to the health of the individual components and parts under consideration, as well as the overall engine (Miljković, 2013; Piancastelli *et al*., 2012).

Knowing the temperature limits of the materials used to manufacture engine components is crucial (Czarnigowski *et al*., 2019). Specifically, the temperatures that engine components experience are not to surpass the so-called critical temperature, as it notes the point of thermal overload – a critical situation which lends the impacted component, and thus the entire engine, out of service (Piancastelli *et al*., 2012). Furthermore, continuous exposure to higher temperatures can ultimately decrease the usable service life of a part or component (Miljković, 2013).

Even though the critical temperature for the manufactured carbon fiber valve covers has not been computed and the temperature limits require further exploration, the lower temperatures the carbon fiber valve cover experienced during the engine run are advantageous. Similarly, the rapid cooling rate observed during the carbon fiber valve cover run allows for a comparatively quick return to lower operating temperatures.

Nevertheless, the rapid heating and cooling rates may potentially introduce limitations. While not inherently the same, the heating and cooling cycles the valve covers are subjected to can be thought of as thermal cycles, where the temperature rises and decreases in a cyclic motion. The composite valve covers experienced significant temperature fluctuations (cycles), while the temperature of the steel valve cover remained more static, with fewer extreme temperature variations. Even though the ability of the carbon fiber valve cover to return to a lower temperature can be advantageous, the continuous temperature cycling- similar to thermal cycles - can be a limiting factor and further reduce the service life of the carbon fiber valve covers (Piancastelli *et al*., 2012).

While no inherent damage was discovered during the visual inspection, the tested carbon fiber valve cover displayed sealing problems (refer to Fig. 8). The leak can be traced back to the geometry of the valve cover. The original, steel valve cover – as highlighted with red arrows in Fig. 10 – presents a raised ridge along the flange, which acts as an additional oil barrier and seal. Due to manufacturing limitations, the valve covers manufactured by Wang *et al.* (2014) did not adopt the ridge along the flange (Fig. 3 and 9). Therefore, the missing ridge is the probable cause for the oil leak rather than inherent deficiencies in the carbon fiber valve cover itself.

While the carbon fiber valve covers evaluated show potential, they do not fully satisfy the requirements of the PMA. The two main points of contention are the severe temperature fluctuations as well as the leak resulting from manufacturing limitations. Nevertheless, the overall lower temperatures experienced coupled with the faster cooling observed on the carbon fiber valve cover would be beneficial to the overall engine operation and health. Moreover, it is important to consider the difference in weight between the two valve covers. With only 36.73 g, the carbon fiber valve cover is significantly lighter than the steel valve cover with 151.62 g. Over a four-cylinder engine, this would result in overall weight savings of 459.5 g. Considering a twin-engine aircraft, weight savings of almost one kilogram could be achieved.

The comparative lower weight of composite materials and subsequent fuel savings is a factor that has contributed to the quick expansion in the use of these materials in the first place (Mouritz, 2012). Additional weight savings achieved by using composite-based parts and components in reciprocating engines in general aviation could further contribute to this trend, and aid in the general push of aviation to lower fuel use and emissions.

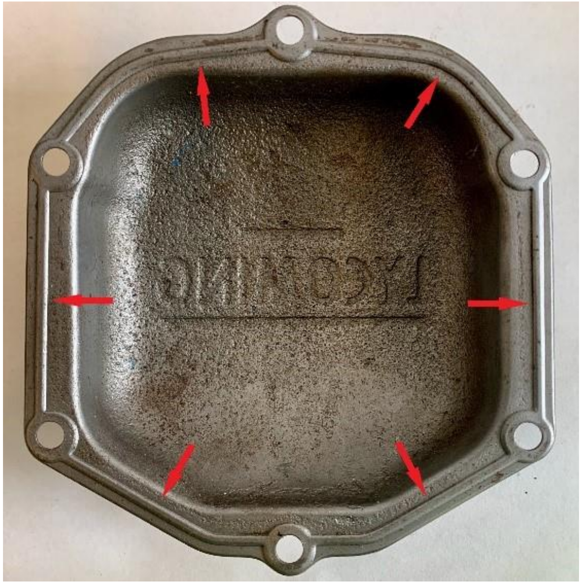

Fig. 10: Sealing ridge on the steel valve cover

Conclusion

In this study, novel carbon fiber valve covers were evaluated for aircraft reciprocating engine applications. Specifically, the FAA-provided PMA procedures were considered to evaluate the potential for carbon fiber valve covers to replace traditionally used, original steel valve covers. The conducted study focused on two specific aspects of the PMA certification, namely (1) engine system and component tests, in the form of a thermal study, and (2) tear-down inspections, in the form of a post-run visual inspection of the carbon fiber valve covers. Moreover, a comparative testing paradigm was followed, as the results from the novel carbon fiber valve cover were compared to those of the steel valve cover. Both valve cover types were installed on cylinder number four of the test engine and subjected to a simulated flight cycle. Temperature results as well as observations from the post-run visual inspection do not indicate direct equivalency in performance between the two valve cover types.

Seven temperature-related data points were evaluated as part of the thermal analysis: Maximum and average temperature (with backwash and post-run), maximum heating and cooling rate (with the effect of backwash), and the heating rate post-run. The steel valve cover experienced higher temperatures than the composite valve cover: On average, the steel valve cover displayed temperatures 6.17°C above the carbon fiber valve cover when the post-run period was considered, and 7.09°C when the post-run period was not considered. The maximum temperature of the steel valve cover was 9.5°C higher than that of the carbon fiber valve cover during the run, and 7°C higher during the post-run period. The carbon fiber valve cover, nevertheless, experienced greater heating and cooling rates under the influence of the propeller backwash. Specifically, the heating/cooling rate of the carbon fiber valve cover equaled 4.33°C/min. The steel valve cover, however, experienced a heating rate of 3.67°C/min. and a cooling rate of 1.67°C/min. Post-run, without propeller backwash, the heating rates for the steel and composite valve cover equaled 18.54 and 8.90°C/min., respectively.

The oil leak discovered during the visual inspection as well as the higher heating rate experienced by the novel carbon fiber valve cover may introduce problems to the engine operation and lifetime, and thus lead to potential performance discrepancies between the two valve cover types. Therefore, based on the performed study, the tested carbon fiber valve cover would not meet PMA certification requirements. However, the carbon fiber valve cover exhibits promising behaviors, such as lower temperature exposure and rapid cooling rates. Coupled with the inherent weight savings achieved through the use of composite materials, the novel valve covers present potential benefits for the application in aircraft engines. With additional studies - especially exploring the areas of future work described below - the advantages presented by the carbon fiber valve covers may be embraced. Similarly, by further refining the valve cover design and tailoring to the operational limitations, the ultimate goal of achieving certification for aircraft application may be achieved.

Potential for Future Work

Even though equivalent performance between the two valve cover types was not directly established, the results obtained highlight the potential for future development in this area. Specifically, further testing and refinement of the carbon fiber valve covers are required to achieve the same operational level as the original, steel valve covers. While lower temperatures were observed during the carbon fiber valve cover run, it is important to compare these temperatures to the temperature limits (Czarnigowski *et al*., 2019) and critical temperature (Piancastelli *et al*., 2012) of the specific composite material used, and explore specific high-temperature behaviors, such as demonstrated by Mohammed *et al*. (2018).

Additionally, as only a visual test was performed after the run, further post-run tests to determine the internal structural integrity and the effect of operational temperature exposure are necessary to establish equivalency between the steel and carbon fiber valve covers. Similarly, further testing at the steady state temperature-following the experimental design provided by Trunzo *et al*. (2012)-is required to establish the durability limits of the newly developed carbon fiber valve covers. These results would be of special interest to show compliance with the endurance limits per the FAA (2009).

Moreover, in real-life scenarios, the valve covers are exposed to various environmental factors, including fluids (i.e., oil), Ultraviolet (UV) light from the sun, and humidity. These factors have the potential to detrimentally impact and degrade composite materials. Subsequently, future testing and research efforts should include exposure tests as outlined per SAE International (2018).

Lastly, as indicated by Wang *et al*. (2014), the individual carbon fiber valve covers manufactured presented differences based on the degradation of the 3D printed mold with repeated uses. Consequently, concepts such as quality assurance and reduced variability in quality between products require further exploration. Specifically, the replicability of the results should be further evaluated by subjecting different carbon fiber valve covers manufactured following the procedures outlined by Wang *et al.* (2014) to the test procedures outlined herein.

Author's Contributions

Both the authors have equally contributed to this manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all other authors have read and approved the manuscript and no ethical issues have been involved.

References

Anoshkin, A. N., Zuiko, V. Y., Pisarev, P. V., Alikin, M. A., & Shustova, E. N. (2018). Mechanical and acoustic research of sound-absorbing composite sandwich structures for aircraft engines. *In 12th International Conference on Sandwich Structures* ICSS-12: Proceedings (No. CONF, pp. 22-24). EPFL-CCLab Composite Construction Laboratory. https://infoscience.epfl.ch/record/256069/files/ICSS-12_Anoshkin-et-al_22-24.pdf

ASTM International. (2021). F3064/F3064M-21 standard specification for aircraft powerplant control, operation and indication. *ASTM International, West Conshohocken*, PA, USA. doi.org/10.1520/F3064_F3064M-21

Beckmann, H. D., & Oetting, H. (1985). Fiber reinforced plastics for lightweight engine parts (No. TP-850520). *Society of Automotive Engineers*, Inc., Warrendale, PA. https://www.osti.gov/biblio/5745325

Buckley, R. T., Stanglmaier, R. H., Radford, D. W., & Willson, B. (2005). *A Prediction of weight reduction and performance improvements attainable through the use of fiber-reinforced composites in IC engines* (No. 2005-01-3693). SAE Technical Paper. https://www.sae.org/publications/technical-papers/content/2005-01-3693/

Chockalingam, M. (2015). *Investigation of the ceramic piston for internal combustion reciprocating engine* (Doctoral dissertation, Kauno technologies universities). https://epubl.ktu.edu/object/elaba:8802974/

Corman, G., Upadhyay, R., Sinha, S., Sweeney, S., Wang, S., Biller, S., & Luthra, K. (2016). General Electric company: Selected applications of ceramics and composite materials. *In Materials Research for Manufacturing* (pp. 59-91). Springer, Cham. https://link.springer.com/chapter/10.1007/978-3-319-23419-9_3

Czarnigowski, J., Skiba, K., & Dubieński, K. (2019). Investigations of the temperature distribution in the exhaust system of an aircraft piston engine. *Combustion Engines*, 58.

FAA, (1964). 14 Code of Federal Regulations [CFR] subpart D-Block Tests; Reciprocating Aircraft Engines. *Federal Aviation Administration*. https://www.law.cornell.edu/cfr/text/14/part-33/subpart-D

FAA. (1980). 14 Code of Federal Regulations [CFR] § 33.55–teardown inspection. *Federal Aviation Administration*. https://www.law.cornell.edu/cfr/text/14/33.55

FAA. (2008). 14 Code of Federal Regulations [CFR] § 33.53–Engine System and Component Tests. Federal Aviation Administration. https://www.law.cornell.edu/cfr/text/14/33.53

FAA. (2009). 14 Code of Federal Regulations [CFR] Part 21–certification Procedures for Products and Articles. *Federal Aviation Administration*. https://www.law.cornell.edu/cfr/text/14/part-21

FAA. (2010). Advisory Circular [AC] 33.91-1–Engine System and Component Tests. *Federal Aviation Administration*. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_33_91-1.pdf

FAA. (2014). Advisory Circular [AC] 21.303-4–Application for Parts Manufacturer Approval Via Tests and Computations or Identicality. *Federal Aviation Administration*. https://www.faa.gov/documentLibrary/mediaAdvis ory_Circular/AC_21.303-4.pdf

FAA. (2018). Type Certificate Data Sheet (TCDS) No. 1E12. *Federal Aviation Administration*. https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgMakeModel.nsf/0/eb163de97780a96b8625827f005b08c4/$FILE/1E12_Rev_10.pdf

Hauser, B. R., Blockus, K. M., & Braly, G. W. (2006). An improved method of accelerated crankshaft fatigue testing for reciprocating aircraft engines. *SAE Transactions*, 689-694. https://www.jstor.org/stable/44657720

Hiken, A. (2017). The evolution of the composite fuselage-a manufacturing perspective. *SAE International Journal of Aerospace*, 10(2), 77-91. doi.org/10.4271/2017-01-2154

Kass, M. D., & Noakes, M. W. (2017). Printing components for reciprocating engine applications. In additive manufacturing handbook: *Product Development for the Defense Industry* (pp. 315-315). CRC Press. doi.org/10.1201/9781315119106

Kassapoglou, C. (2013). Design and analysis of composite structures: With applications to aerospace structures. *John Wiley and Sons*. ISBN-10: 1118536940.

Killough, D. L. (1996). Pilot's Operating Handbook and FAA-approved airplane flight manual: Piper PA-30 Twin Comanche, *Aircraft Publications*, *Austin*, TX, USA. http://flygateway.org/wp-content/uploads/2020/03/Piper-PA-30-C-FCDI.pdf

Kumaraswamy, J., Kumar, V., Purushotham, G., & Suresh, R. (2021). Thermal analysis of nickel alloy/AL2O3/TIO_2 hybrid metal matrix composite in automotive engine exhaust valve using FEA method. *Journal of Thermal Engineering*, 7(3), 415-428. doi.org/10.18186/thermal.882965

Lycoming. (2006). Operator's Manual-O-320 Series (Part No. 60297-30), Lycoming, Williamsport, PA, USA. https://www.lycoming.com/sites/default/files/O-320 Operator Manual 60297-30.pdf

Ma, J., Shen, L., & He, Y. (2017). Application of composite materials in the engine. Materials Science: *Advanced Composite Materials*, 1(1), 1-9. https://core.ac.uk/download/pdf/230064854.pdf

Marsh, G. (2012). Aero engines lose weight thanks to composites. Reinforced Plastics, 56(6), 32-35. doi.org/10.1016/S0034-3617(12)70146-7

Miljković, D. (2013, May). Engine fault detection for piston engine aircraft. *In 2013 36th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)* (pp. 874-879). IEEE. https://ieeexplore.ieee.org/abstract/document/6596380/

Mohammed, I., Talib, A. A., Sultan, M., & Saadon, S. (2018). Thermal properties of HL002-TA/B epoxy resin/hardener in fiber metal laminates composites for aero-engine. *Compos Int J Pure Appl Math*, 119(15), 3761-3769. https://acadpubl.eu/hub/2018-119-15/2/397.pdf

Mouritz, A. P. (2012). Introduction to aerospace materials. *Elsevier*. doi.org/10.2514/4.869198

Piancastelli, L., Frizziero, L., Marcoppido, S., & Pezzuti, E. (2012). Methodology to evaluate aircraft piston engine durability. *Int. J. Heat Tech*, 30(1), 89-92. https://www.iieta.org/sites/default/files/Journals/IJHT/30.1_13.pdf

SAE International. (2018). Environmental Degradation of Composite Materials (ARP6287). https://saemobilus.sae.org/content/ARP6287/

Trunzo, M., Schubbe, J., Graham, S. M., & Caton, P. (2012, November). Integration of Carbon Fiber Composite Materials into Air-Cooled Reciprocating Piston Engines for UAV Applications. *In ASME International Mechanical Engineering Congress and Exposition* (45196, pp. 943-956). American Society of Mechanical Engineers. https://asmedigitalcollection.asme.org/IMECE/proceedings-abstract/IMECE2012/943/288972

Wang, P. H., Kim, G., & Sterkenburg, R. (2014). An Evaluation on the Effectiveness of a 3D Printed Composite Compression Mold. *International Journal of Architectural and Environmental Engineering*, 15(1), 52-56.

Woś, P., & Michalski, J. (2011). Effect of initial cylinder liner honing surface roughness on aircraft piston engine performances. Tribology Letters, 41(3), 555-567. https://link.springer.com/article/10.1007/s11249-010-9733-y