Experimental Investigation of a Mini Turbofan Engine with Respect to Turbojet for its Thrust Modulation

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A thesis submitted in partial fulfillment of the requirements for the degree of

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Thesis Supervisor:

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MASTER THESIS WORK

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Dedicated to my beloved Parents and all well-wishers who remained faithful and trust-worthy during this time

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Abstract

Gas turbine engines have been used in power houses, ships and aircrafts in general for propulsion. They are extremely powerful for their size and have very high thermal efficiency. Large airliners and military aircrafts use turbofans while small scale aircrafts such as mini UAVs and ultralight jet still use turbojets which are not as fuel efficient as turbofans. The purpose of this research is to investigate whether a mini turbofan should be developed for UAVs or not. Would it be more fuel efficient than the similar sized-turbojet as is the case in large scale turbofans?

For this purpose, a mini turbofan was developed by taking off-the-shelf turbojet, installed a fan on the turbojet via a secondary turbine and a gearbox. A K60-TP engine manufactured by KingTech was used. A fan was attached to the engine inside a shroud and mounted on a test stand. The engine was run at different throttle positions where the fan's RPM, fuel consumption, and thrust were recorded. With the available data, the Thrust Specific Fuel Consumption (TSFC) was calculated and was compared to a turbojet of the comparable size and thrust.

It was observed that the turbofan came out to be 38% more fuel efficient than the turbojet. The results indicate that a mini turbofan would be more economical to operate than a turbojet of its comparable size, hence development of mini turbofan engines for commercial purpose is desirous. Mini turbofans, if commercially produced, would eventually phase out mini turbojets currently in use.

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1 INTRODUCTION

1.1 Emergence of UAVs and Ultralight Jets

Aviation is an ocean with vastly unexplored pearls. It is the latest and the fastest means of transportation for the mankind, from carrying cargo to humans from one place to another in only a matter of minutes and hours, time which previously was considered impossible. Earlier, the aircrafts were slower, heavier relative to its size, having low service ceiling and limited performance, inefficient and had poor fuel economy. Modern aviation has come a long way since its inception, with the development of more powerful, efficient, economical, larger yet lighter aircrafts. However, this does not end here, rather it's the beginning of a new era. Aircrafts have started to become pilotless and are called Unmanned Aerial Vehicles short termed as UAVs. With the advent of UAVs, a new chapter in the field of aviation has opened. Primarily, the UAVs were designed for military purposes to be used in warzones without risking the life of a pilot.

UAVs have now become commercialized and are being used in various fields and environments. They are being successfully used as agricultural drones for crop-dusting, fire-fighting drones for taking out forest fires in the wild, surveillance and terrain mapping in hard-to-reach areas, supplying medical aids to remote areas and much more.

Other than the UAVs, ultralight amateur-built aircrafts have also been warmly welcomed in aviation market for their smaller size and affordability for personal commutes. They however are propeller-driven (slow flyer) or turbojet powered (fast flyer) which are extremely inefficient and are heavy on fuel consumption. This creates a need to have a turbofan engine for such league of aircrafts.

1.2 Limitations of UAV designs and performance due to power plants

Till now, the UAVs have been used for military purposes and were quite larger in size. With the advancement in technology and new materials available to manufacture an aircraft, modern UAVs have shrunken to a size of small car, meaning that they weigh less and need less power to be able to remain airborne. The performance of an aircraft is hugely dependent on the engines other than the aerodynamics of the vehicle. Even if the aircraft is aerodynamically efficient but the engine that it carries to power itself is heavy and inefficient, then the overall efficiency and the performance of the vehicle reduces vastly. Modern commercial airliners are able to fly up to a distance of greater than ten thousand kilometers carrying hundreds of passengers without refueling all because of efficient engines and aerodynamic designs. The engines that are most commonly used today in modern jets are turbofan engines which produce enormous amount of thrust and consume very less fuel. They have low specific fuel consumption and are thermally more efficient than reciprocating engines. These engines have high thrust to weight ratio than the turbojet engines. Turbojets have almost been phased out since they are inefficient and noisy.

Unfortunately, we do not see any commercially available small-scale turbofan engine in the market that could potentially power small-scale aircrafts such as light personal jets or UAVs. With this limitation, it is very much obvious that the process of improvement in designs and enhancement in the performance of the UAVs and ultralight jets would be hindered.

Figure 1: *TST-14 Glider Jet*

1.3 Motivation for this research and possible benefits.

After analyzing the emerging market of the UAVs and small-scale aircrafts, we have established a vision that a research be carried out to find out why a mini turbofan engine has not been developed yet? And if it has been, why there is no mini turbofan engine available in the market? And if no engine is available, can a prototype be made, and study be conducted to find out its feasibility? Is it feasible to commercially develop and operate a mini turbofan engine? All these questions are yet unanswered and need to be addressed.

With a mini-turbofan engine available, a boost is expected in the UAV market. More efficient, lighter and compact UAVs and aircrafts can be developed with greater payload capacity. Performance numbers would increase for such aircrafts with greater endurance, enhanced range, higher ceilings and speed.

It is pertinent to note that small-scale engines for UAVs and Radio-Controlled Aircrafts, otherwise known as RC-planes, such as mini turbojets, turboprops and reciprocating engines are already available and have been in operations for years around the globe, however, they all have severe limitations in performance. Turbojet engines are far less efficient and consume lots of fuel thus limiting the range and endurance of the aircrafts. The reciprocating engines though consume relatively less fuel as compared to turbojets but are much heavier and have low power to weight ratio. Turboprops on the other hand are smaller and lighter, but the use of propellers restricts them from using for high speed flights. Also, engines such as turboprops and reciprocating engines cannot be used on stealth aircrafts since propellers cannot be housed inside of the aircraft. This leaves turbofan engine the only suitable option for high speed flights with lower fuel consumption, higher thrust to weight ratio, low noise and potential use in stealth aircrafts.

Figure 2: *SubSonex Jet Powered by PBS TJ-100*

1.4 Scope of work

This research addresses the concerns of global aviation market of not having a miniature turbofan engine currently by aiming to conduct a feasibility study based on experimentations by developing a prototype of a mini-turbofan engine. It is highly anticipated that a mini turbofan engine would create a positive impact on the market for UAVs and light personal jets the way a turbofan engine did for the commercial aviation.

2 LITERATURE REVIEW

2.1 Gas Turbine Engines

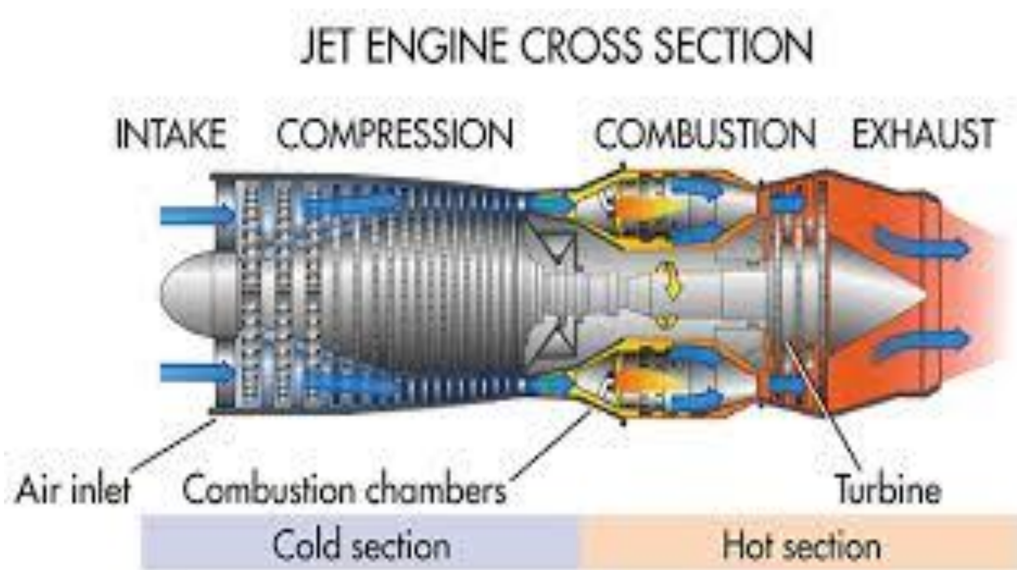


Figure 3: *Illustration diagram of a jet engine*

Gas turbine engines are a type of internal combustion engines, also known by the name of air breathing engine, reaction engines or simply jet engines. These engines are based on the Newton's Third Law of Motion in a way that they expel a mixture of hot gases and air from the rear end thus generating thrust force as reaction. This thrust force is responsible for propelling the aircraft in forward direction. The working principle of these engines is Brayton Cycle and are run as open cycle for thermodynamic analysis.

Compared to other engines, jet engines are extremely powerful for their size. They are designed to operate at higher temperatures thus resulting higher thermal efficiency. Unlike the car engines which are designed for economy at lower RPMs, jet engines are more efficient at high RPMs and typically run at peak power for hours without any trouble.

The operation of a jet engine is fairly simple where air is drawn in through the inlet and is directed to the compressor which then compresses the air instantly to a very high pressure. The sudden rise in pressure also increases the temperature of the air tremendously. The next stage is the combustion chamber, which contains flame holder where flame is held and not allowed to escape to the other components of the engine. The air just before entering the combustion chamber, is high pressure and high temperature. This high pressure and hot air is mixed with fuel and ignited in the combustion chamber increasing the temperature to above 1000^{o}C. This mixture of hot gas and air is then transferred to the next stage where they are passed through the turbine. Turbine draws some of the power from hot gases to keep the compressor running. The remaining amount of hot gases are then ejected at the end of the engine via nozzle, creating thrust as reaction and propelling the aircraft forward.

Figure 4: *General Electric GE90-115B*

2.2 Compressor

Compressors are turbomachines that perform work on the working fluid and transfer energy to it by increasing the pressure. Compressors must not be confused for pumps as the latter employs liquids as working fluid while the compressors use gas as working fluid, however, the working principle remains the same for both. There are several types of compressors, however, only the ones used in jet engines will be discussed here. Those types primarily are axial flow compressors and radial compressors, also called centrifugal compressors.

2.2.1 Axial Compressor

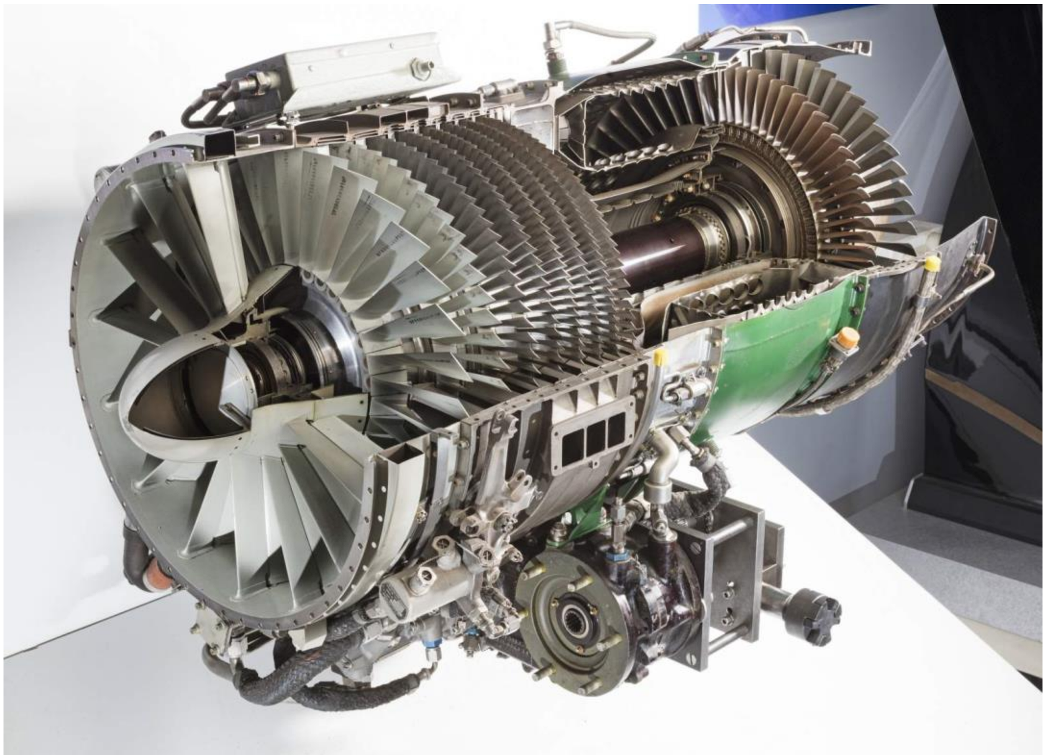


Figure 5: *General Electric j85-GE-17A Turbojet Cutaway (a)*

Most modern high-end aircrafts use jet engines that employ axial compressors. Axial compressors use a set of blades called rotor, attached to a hub much like a fan that rotates around a shaft at very high speed and a set of blades called stator which remains stationary. The profile of the blades is shaped like an airfoil which creates pressure difference and diverts the air from the front of the rotor to the back of it at high speed. After exiting the rotor, this high-speed air then immediately strikes the next set of blades called stator and gets slowed down thus the pressure here is increased. Stators are also called diffusers since they diffuse the incoming fast air to slow-moving and high-pressure air.

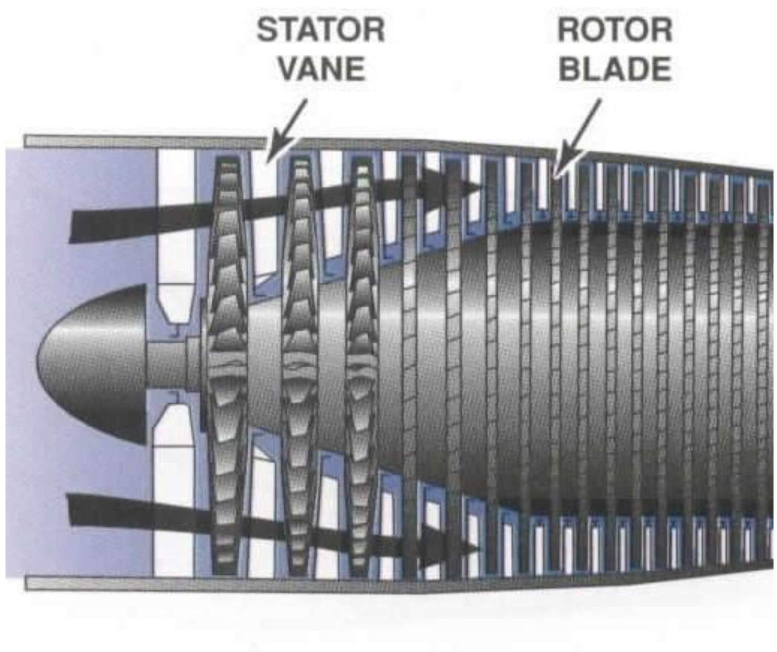


Figure 6: *Illustration diagram of compressor with rotor and stator vanes*

In compressors, stators are used immediately after the rotors and this combination of rotor and stator is called a stage. Axial compressors give very poor results when used with only single or two stages of compression, therefore often employ high number of stages typically thirteen to fifteen for better performance. Axial compressors with multiple stages are more powerful, giving very high-pressure ratios and are more efficient than the radial compressors. First stage in the compressor is the largest and it gets smaller in size with each next stage.

Axial compressors though are efficient, consume lots of power and are very difficult to start. This shortcoming has now been overcome by splitting the compressor in various stages called spool. Modern commercial jet engines use axial compressors with as much as seventeen stages in typically three spools. Spool of the earlier stages of compressors is called low-pressure spool, followed by the intermediate-pressure spool and high-pressure spool at the end.

2.2.2 Centrifugal or Radial Compressor

These compressors work in a slightly different manner than the axial compressors by redirecting the incoming air radially outwards. The design of centrifugal compressor is such that the air is drawn in from the front and redirected outwards centrifugally by rotating the rotor. The high-speed air is then imparted to the stator where it gets slowed down by means of increasing the cross-sectional area thus increasing the pressure as well.

Figure 7: *Centrifugal compressor disc*

Centrifugal compressors deliver superior performance in a single stage, however, when installed with multiple stages, they fail to enhance the performance by considerable margin. Adding more stages increases the weight and cost of the compressor with slight increase in performance, hence, leaving it to axial compressors where high-pressure are required. Their construction is simpler than the axial compressors and are more suitable for light applications such as light aircrafts and auxiliary power units.

2.3 Turbines

Turbines are the opposite of compressors in a way that they extract the energy from the fluid. There are numerous types of turbines, however, only the one used in jet engines will be discussed here, that is, the axial turbine. As indicated by the name, the gas enters and exits the turbine axially similar to axial compressors. Power generated by the turbine is used to rotate the compressor which is mounted on the same shaft in the engine.

Figure 8: *Turbine blade disc of CFM-56 engine*

Much like the axial compressors, axial turbines are also employed in multiple stages for added efficiency and power generation. As discussed earlier that the multi-stage axial compressors have been split into multiple spools to overcome the issue of starting torque, the turbines have also been split into multiple spools. Contrary to compressors, turbines have the stator first and then the rotor. The stators are also called inlet guide vanes or IGVs in-short which guide the incoming air to the inlet of the rotor blade of the turbine.

The efficiency of the gas turbines is limited due to materials unavailable to withstand higher temperatures. Gas turbines operate at very high RPMs subjecting the blades to severe centrifugal loads and stresses with temperatures reaching 1000^{o}C and even above where most of the materials melt. High stresses when combined with melting temperatures could be catastrophic for the turbines therefore require special alloys that could withstand such high structural and thermal stresses. Temperatures at the inlet of the turbine, referred to as Turbine Inlet Temperature (TIT) could reach as high as 1300^{o}C. Though higher TIT is desired since it increases the efficiency of the turbines, they are limited due to materials.

2.4 Turbojets

Turbojets are a type of gas turbine engines and were the first to be used as jet engines. In turbojets, all the air is passed into the core for combustion and expelled out at high-speeds which creates thrust. Since rushing gases are hot enough, they carry much of the heat energy as waste from the system to the environment making the turbojet inefficient for subsonic and transonic flights. Turbojets are considered obsolete and have been replaced by more efficient turbofan engines.

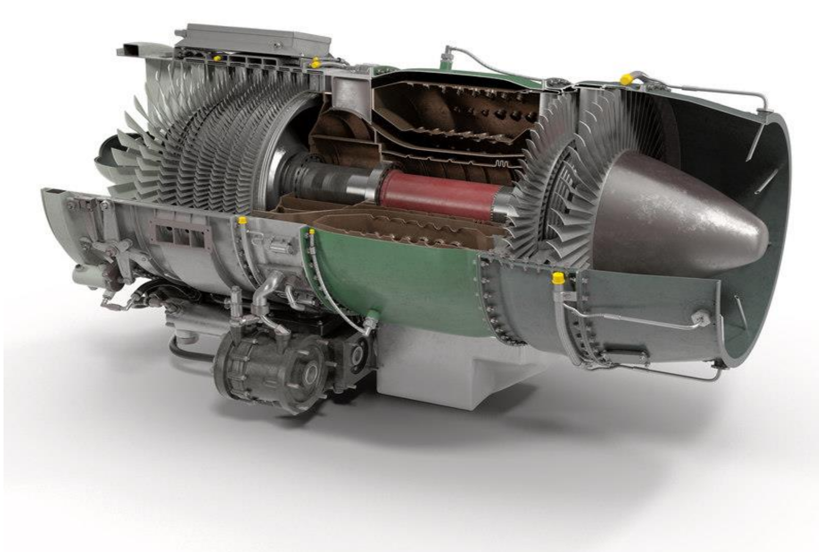


Figure 9: *General Electric J85-GE-17A Turbojet Cutaway (b)*

2.5 Turbofans

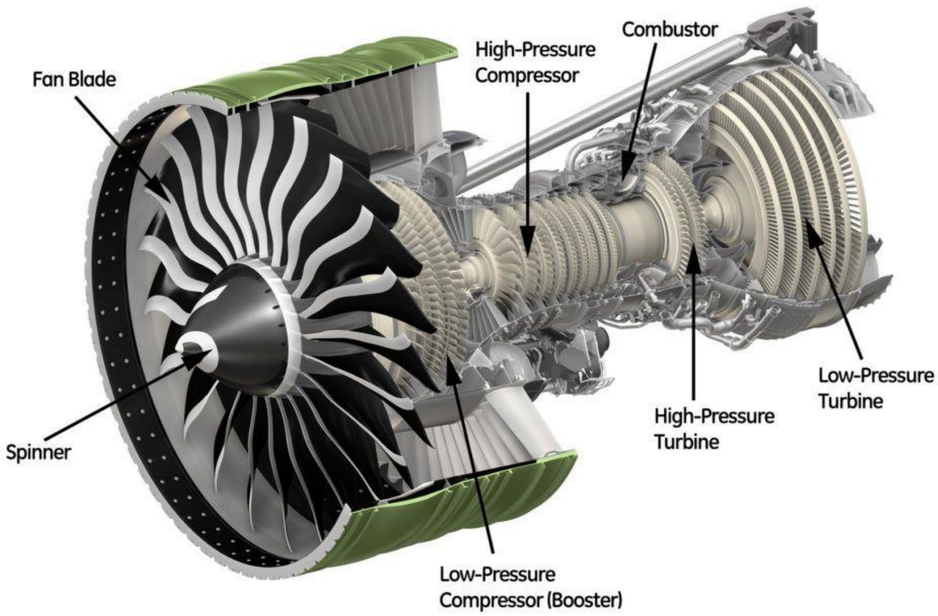
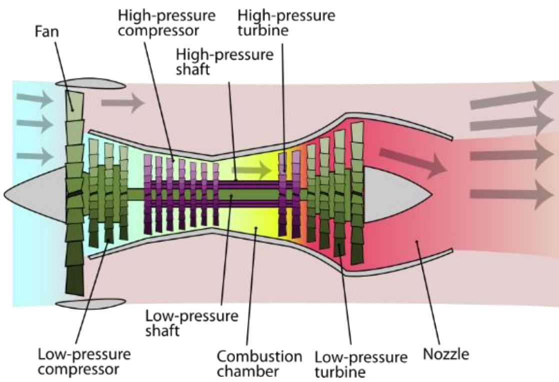


Figure 10: *Illustration of GE90 Jet Engine*

Of many types of gas turbine engines, turbofans are the latest designs that are more powerful and efficient than the turbojets. Turbofans have a large fan in the front that produces most of the thrust instead of the hot rushing exhaust gases. Of all the air that enters the engine, only a portion of it is drawn into the core for combustion and the rest is by-passed around it. Using less amount of air for combustion means less fuel is consumed, hence giving better fuel economy. Turbofans are basically turbojets with by-pass duct.



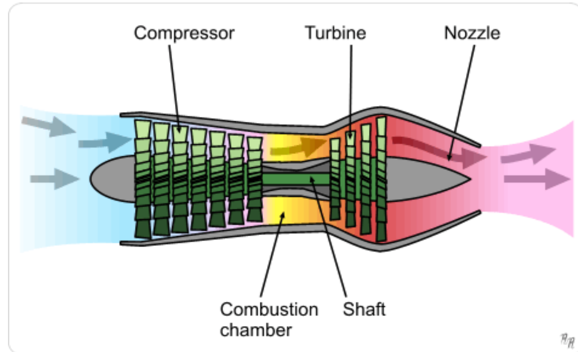


Figure 11: *Turbofan engine*

Figure 12: *Turbojet engine*

Turbofans employ more turbine stages than the turbojet to extract maximum energy from the exhaust gases which then drives the main front fan which creates thrust. Most of the air that is accelerated by the fan is by-passed around the core which keeps the core temperatures in limits and provide cooling effect. This by-passed air around the exhaust gases provide shielding effect and makes the turbofan engine less noisy as compared to a turbojet.

Turbofans used in fighter jets are low-by-pass ratio in which more air is drawn into the core for combustion whereas turbofans used in commercial airliners are high-by-pass ratio engines that bypass more air around the core.

2.6 Turboprops

A propeller when installed on a gas turbine becomes a turboprop engine. The difference between turboprop and turbofan is that the former uses a propeller without a duct around it instead of a ducted fan. Earlier, propellers were driven by piston engines which were heavier but have now been mostly phased out by turboprops due to the latter being superior in terms of thrust to weight ratio.

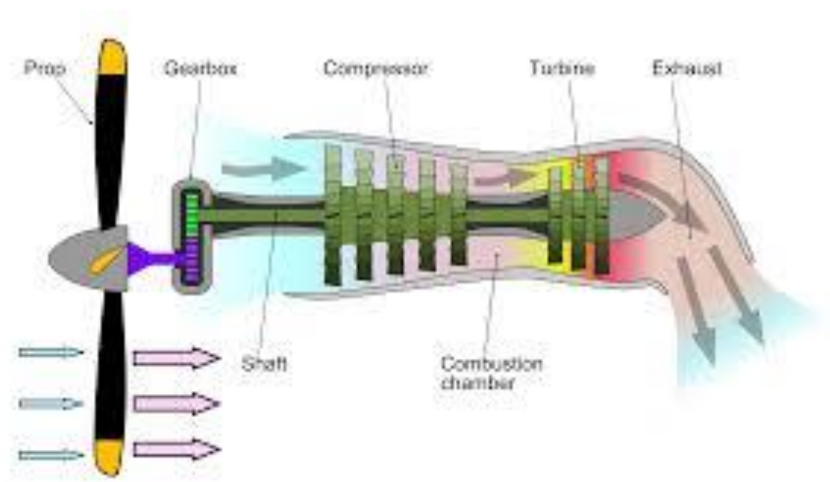


Figure 13: *Turboprop engine*

The propeller is attached to the core via a gearbox that reduces the RPMs and increases the torque which in turn allows for a larger propeller to be used. The larger propeller accelerates more air at lower velocities for a given amount of thrust making the turboprop suitable for low-speed flights.

2.7 Turboshafts

Turboshafts engines are a type of gas turbine engine that do not produce thrust, instead all the power is delivered to the shaft which drives other machinery. Turboshafts are mostly designed using the radial compressors since they are not required to produce thrust at all. Most commonly these engines are used in helicopters to rotate the main and tail rotors via a high-reduction gearbox. Other applications include boats, ships, tanks, and auxiliary power units (APU). Turboshafts are used with high-reduction gearbox which reduces the RPMs and increases the torque significantly thus allowing for use with higher loads.

2.8 Bypass Ratio

Bypass ratio is defined as the ratio between the amount of air bypassed around the core and the amount of air drawn into the core for combustion. The higher the bypass ratio, the less fuel is consumed for producing the same amount of thrust. Most modern airliners' turbofan engines have bypass ratios as high as 80% and more.

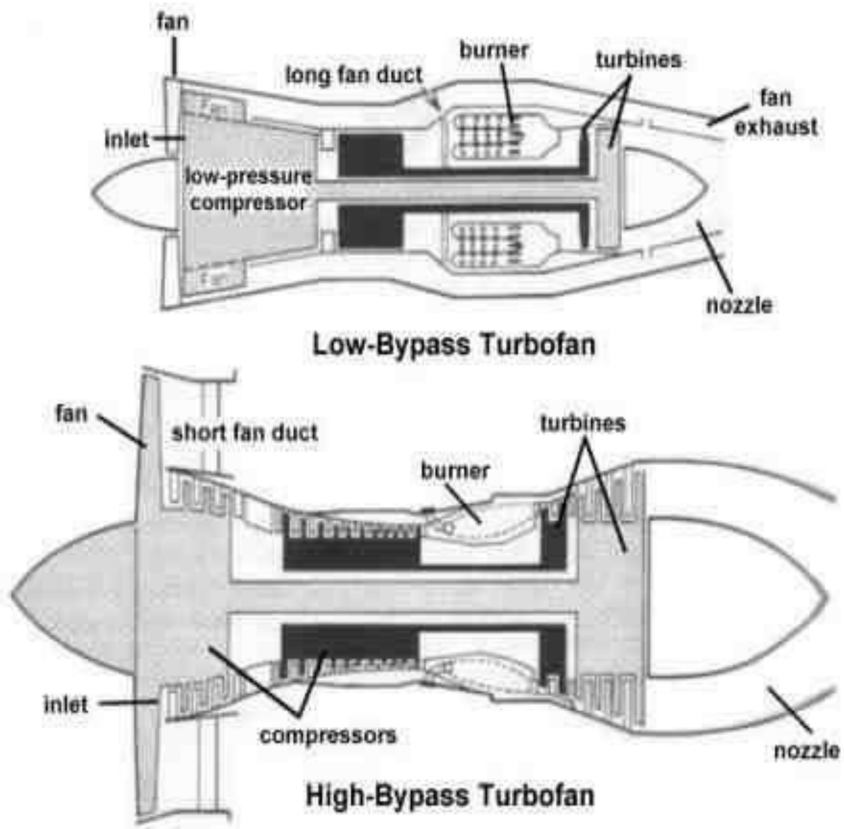


Figure 14: *Diagram showing the difference between low by-pass and high by-pass turbofan engine*

2.9 Thrust

The force that is produced in reaction to propelling the air and/or exhaust gases from the nozzle of the jet engines, is called thrust. The direction of the thrust is always in the direction of flight. Newton's third law of motion states:

$$F=ma$$

$$F=\dot{m} \times v$$

$$F=\text{mass flow rate} \times \text{velocity}$$

From the above equation, it can easily be learned that when mass of air is accelerated, it produces thrust. Thrust can be produced by either increasing the mass flow rate or by increasing the velocity of the air. For low speed applications, velocity can be kept low allowing for higher mass flow rates for the same amount of thrust as demonstrated by turboprops and high-bypass ratio turbofans.

2.10 Thrust Specific Fuel Consumption

The amount of fuel consumed per unit of time per unit of the power produced is called Specific Fuel Consumption. When the power is replaced by thrust and the fuel consumption is measured in terms of thrust instead of power, that is, mass of fuel required to produce thrust for a given time, it become Thrust Specific Fuel Consumption or TSFC.

$$\text{TSFC}= \frac{mass\ flow\ rate\ of\ fuel}{thrust}$$

The units are expressed in grams, second and Kilonewtons i.e. g/(s.KN)

The engines that have higher bypass ratios have lower TSFC however that is not the only major factor; higher pressure ratios and TIT along with efficient turbines overall contribute to lower TSFC.

3 WORKING METHODOLOGY

3.1 Objectives

Since the primary objective of this research is to find out the feasibility of developing a miniature turbofan engine, it is not wise to pour huge amount of money straight away in designing the entire turbofan engine from the scratch. Instead, slightly different approach is taken where different components are taken off the shelf. These components are then modified and transformed where required into the assembly of the turbofan engine. Doing so, has reduced the cost of R&D and saved the time immensely. An off the shelf turboprop engine and a fan is taken and assembled and transformed into a turbofan engine. A duct is installed around the fan with the clearance between the blade tip of the fan and the duct as tight as possible which is less than 1mm in order to avoid the creation of tip vortices.

Following are the core objectives of this research:

1. Construct a WORKING model/prototype of turbofan engine.
2. Select a suitable fan size for the engine based on the data available for the engine. (Engine RPM, power, etc.)
3. Measure the thrust and fuel consumption of the engine at different RPMs.

3.2 Equipment

Initial cost of R&D for this project is estimated to be nearly 1.5 million rupees comprising of several components such as engine, fan, duct, test-stand and many other accessories. Out of all these, only major and critical components for this project are mentioned below and discussed in detail.

3.2.1 Engine

Figure 15: *KingTech K60-TP*

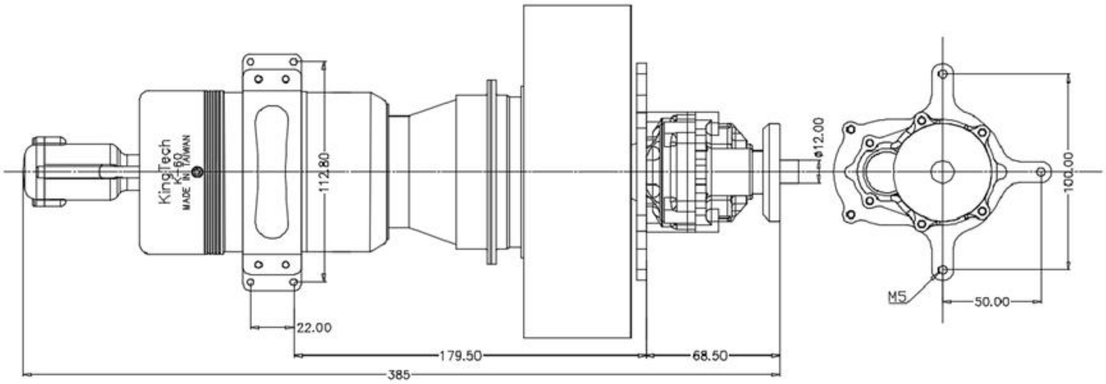
The engine used in this project is a turboprop modeled as KingTech K-60TP manufactured by KingTech Turbines. This turboprop engine is derived from K-60G2 turbojet engine by the addition of a secondary turbine and a high-reduction gearbox to the turbojet. There are other turboprops available from different manufacturers as well however, cost was a major factor in addition to other factors such as reliability and after sales service in the selection of this engine.

The selection of a turboprop has been beneficial since it already incorporates a secondary turbine mated to a gearbox, therefore eliminating the need to use independent turbojet and gearbox, saving us time.

The specifications of the engine are given below:

Length	385mm
Weight	2400g
Maximum RPM (core)	160000
Maximum RPM (propeller/fan)	8500
Exhaust Gas Temperature EGT	700°c
Fuel Consumption @ max throttle	240g/min
Lubrication	5%
Fuel Used	Diesel, Jet A1, Kerosene

Table 1: *Specifications of KingTech K60-TP*



RPM	PWR (KW)
2000	3.9
2500	4.6
3000	5.2
3500	5.7
4000	6.1
4500	6.5
5000	6.8
5500	6.9
6000	6.9
6500	7.1
7000	7.3
7500	7.1
8000	7.0
8500	6.4

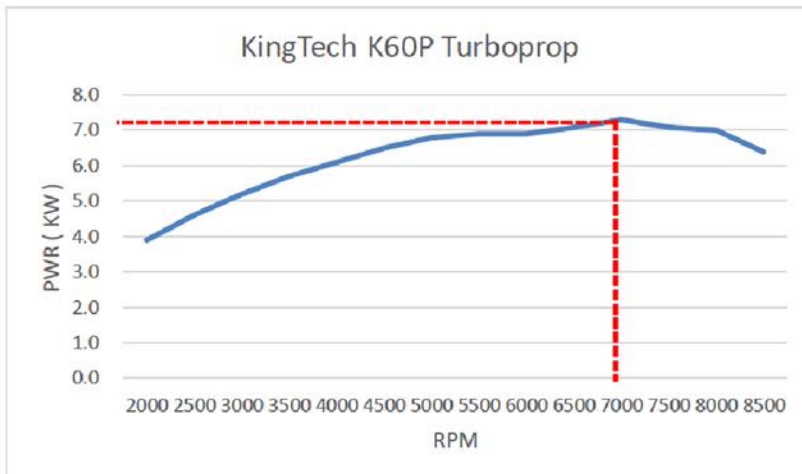


Figure 16: *Power curve of K60-TP obtained from the engine manual*

3.2.2 Fan

The fan for the engine was selected from the market rather than designing and manufacturing our own. Doing so helped us in saving time and reducing R&D cost, also eliminating the need to balance the fan at high speed since fan from the market already came balanced. The selection of fan is dependent upon different parameters such as engine RPMs, power requirement and weight of the fan.

Three fans were shortlisted from the market.

Description	Fan 1	Fan 2	Fan 3
Rotor Dia. (inches)	16”	18”	20”
Rated RPMs	5500	5500	5500
Rated Power (kw)	5.6	8	10.5
Weight (Kg)	1.6	2.4	3.8
Material	Cast Iron	Cast Iron	Cast Iron
No. of blades	8	8	8

Table 2: *Description of the fans*

Since the K60-TP engine power is approximately 7 kilowatts, therefore fan 2 and fan 3 are not suitable as they exceed the power requirement and are quite heavy.

Figure 17: *Fan used in this experiment*

Specifications of the fan:

Specifications	**Values**
Tip Dia. (mm)	406
Hub Dia. (mm)	127
Number of blades	8
Duct Dia. (mm)	410
Tip clearance (mm)	2
Blade root angle (degrees)	64
Blade tip angle (degrees)	32
Blade chord at root (mm)	50
Blade chord at tip (mm)	30

Table 3: *Details of the selected fan*

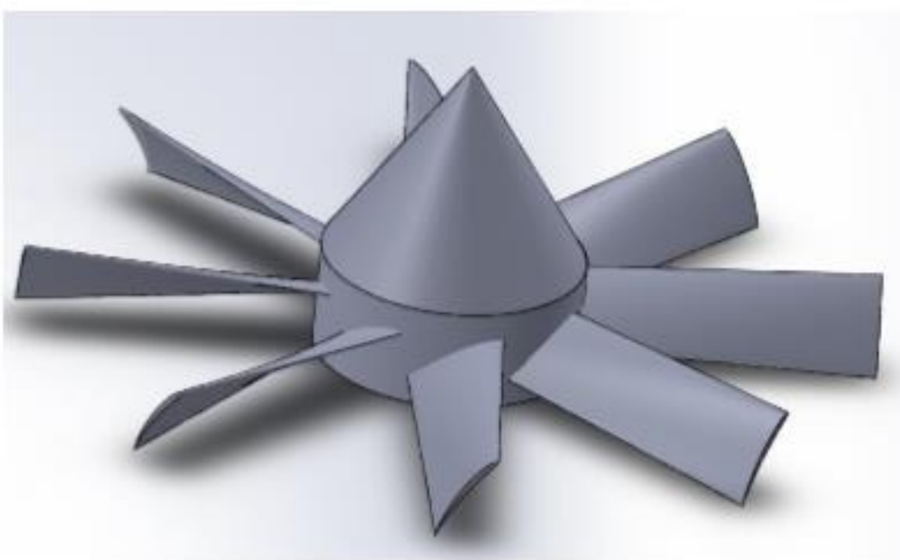


Figure 18: *CAD model of the fan*

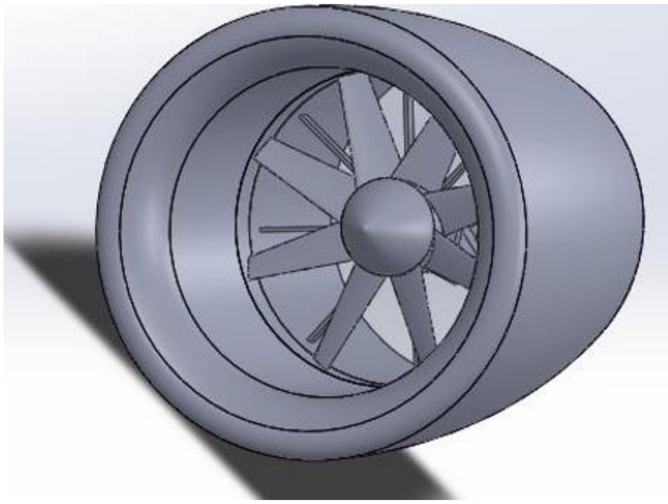


Figure 19: *CAD model of the fan and engine installed in the duct*

A 3D CAD model of the fan was made and analyzed for its potential thrust. This was done in order to determine whether the fan selected was suitable for the purpose and develop any thrust or not.

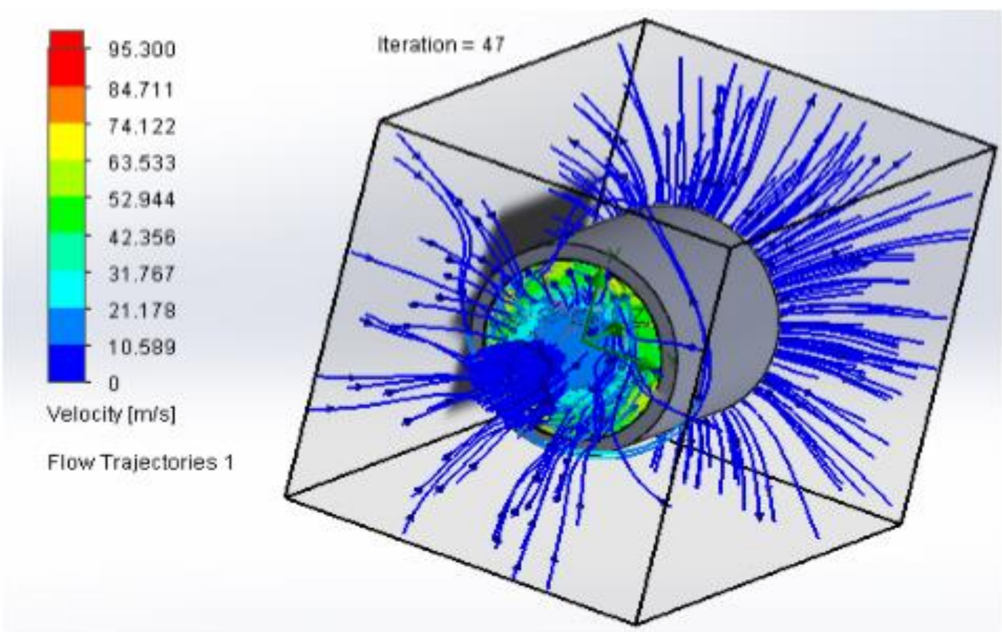


Figure 20: *Flow Simulation analysis on the fan*

The analysis was done using SolidWorks Flow Simulation. The approximate thrust was found out to be 53N at sea level conditions.

3.2.3 Shroud

The construction of shroud is of critical importance as it must be strong enough to house the machinery inside of it and withstand the thrust force. Also, the tip clearance between the fan and the duct must be uniform and minimal throughout the circumference.

Figure 21: Secondary frames used to hold the ribs in place

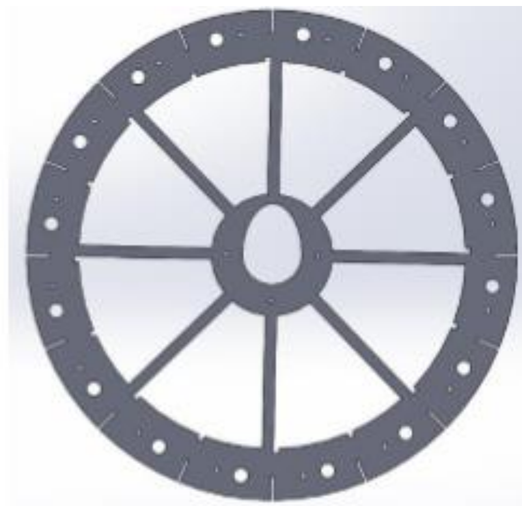


Figure 22: Primary frames used to bear the load

Manufacturing a duct out of metal for this size can be costly and would be very heavy making it nearly impossible to be man-handled. The shroud was constructed out of 3mm ply-wood, fiberglass, and carbon fiber. The use of composite materials makes the duct lightweight yet very strong.

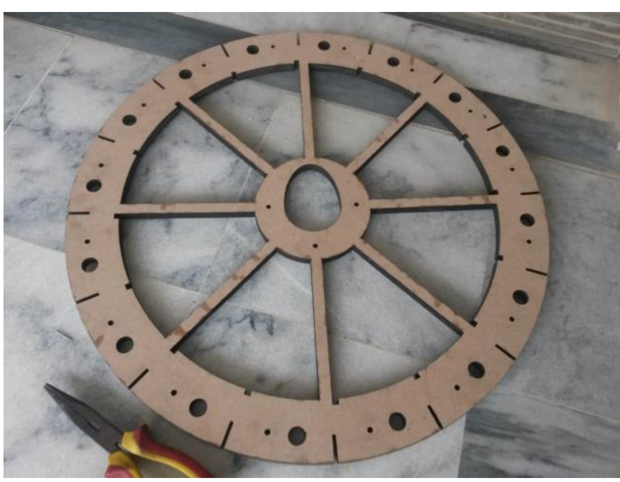


Figure 23: Circular frames (a)

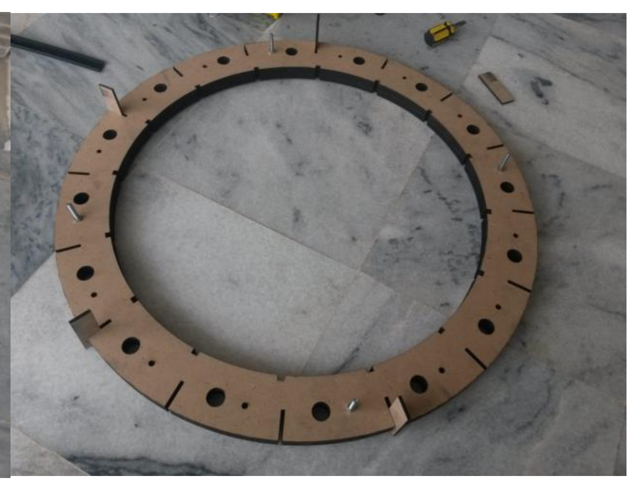


Figure 24: Circular frames (b)

Figure 25: *Shroud structure (c)*

Figure 26: *Shroud structure (d)*

The ribs (longitudinal frames) and cross-sectional frames were laser-cut from the ply-wood and were joined together using epoxy resin. The purpose of the ribs is to maintain the cross-sectional area of the duct throughout its entire length whereas the cross-sectional frames are used to hold the ribs together in their place.

Figure 27: *Composite material applied (a)*

Figure 28: *Engine and fan installed (b)*

Once the structure was ready, fiberglass and carbon fiber were applied on the inner walls of the duct with epoxy resin. This was done to strengthen the walls of the duct and protect the ply-wood from getting any damage during the operation of the engine.

3.2.4 Test Stand

A test stand is where an engine is mounted on. A test stand is used when the engine needs to be tested outside of an aircraft. For our research purpose we had to construct our own test stand as no test stand was available to our custom-made turbofan engine.

Figure 29: *P9010e Turbojet Engine Test Stand by Cussons Technology*

Test stands can be of different setups as per the requirements. The more the variable of an engine that needs to be measured, the more sensors and complexities it involves.

Our requirement is to measure thrust, fuel consumption in grams per second and rpm of the fan, however, the fuel consumption and the rpm of the fan are logged-in by the ECU (Engine Control Unit), thus, making it much simpler for the stand as it only needs to measure thrust.

Other consideration while constructing a test stand was that it should be able to mount not only the turbofan but also a turbojet and turbofan of the similar size.

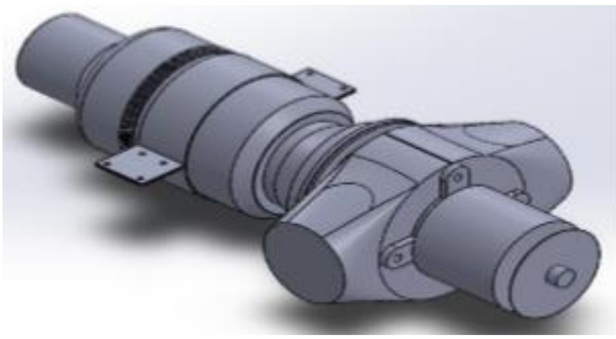


Figure 30: *CAD model of the K60-TP (a)*

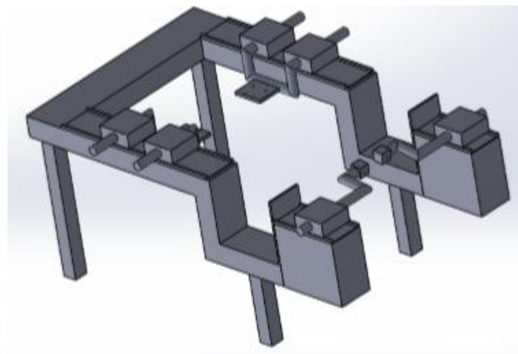


Figure 31: *Initial concept of the test stand (b)*

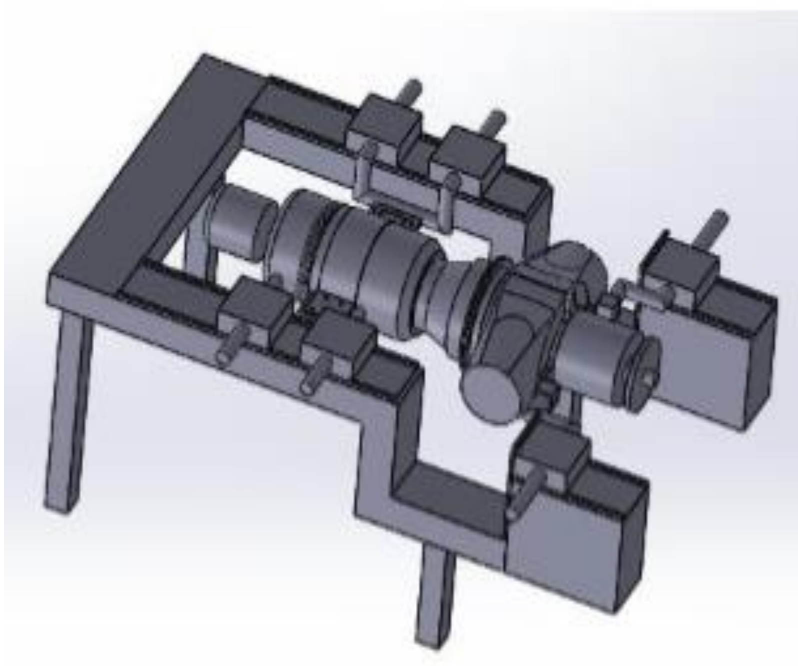


Figure 32: *engine installed on the test stand (c)*

An initial 3DCAD concept of the test stand was made however it immediately required amendments as the initial concept could not mount the custom-made turbofan. It was noted that for the turbofan and turboprop engines, the slider-based test stand was not favorable because of the larger diameters of turboprops and turbofans.

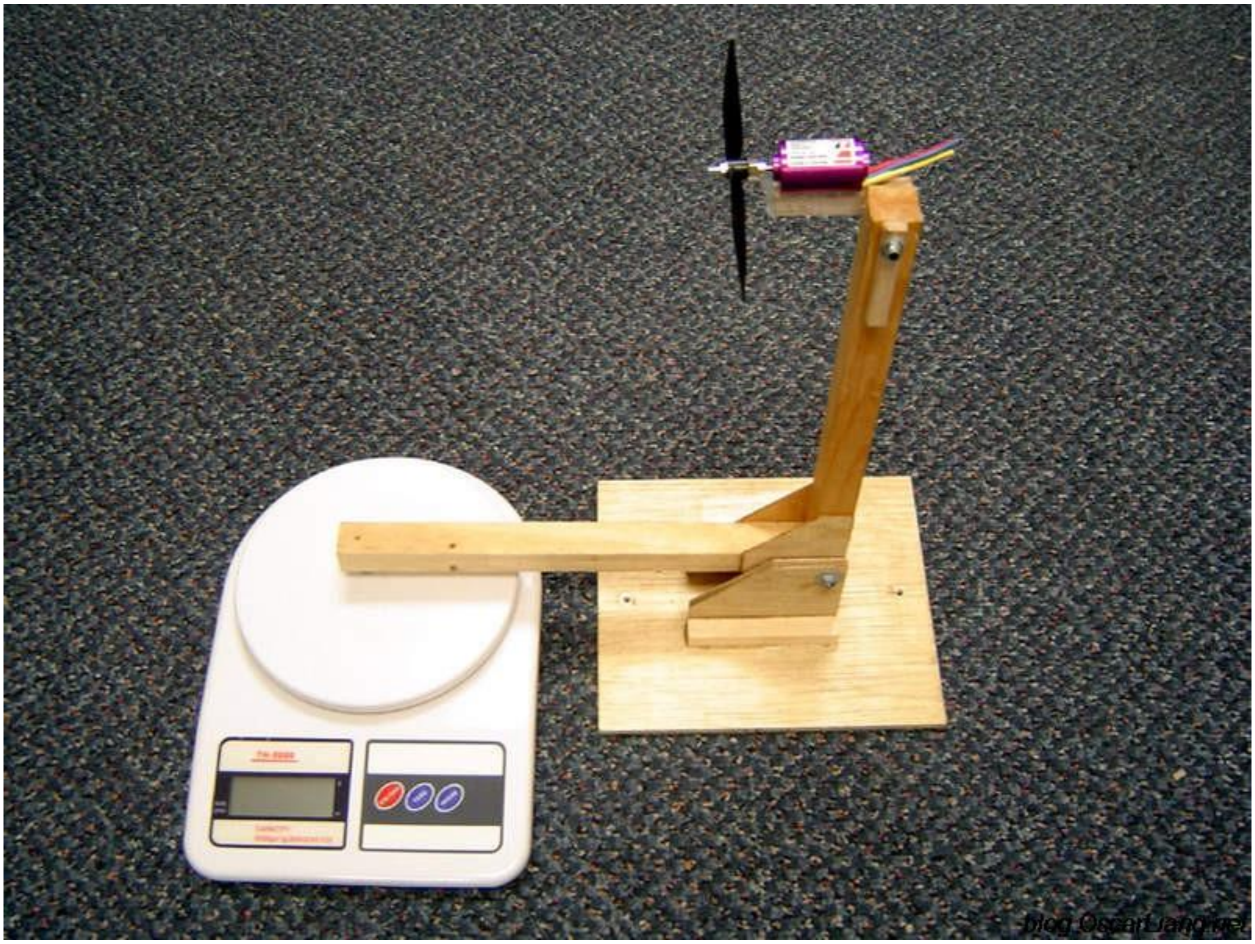
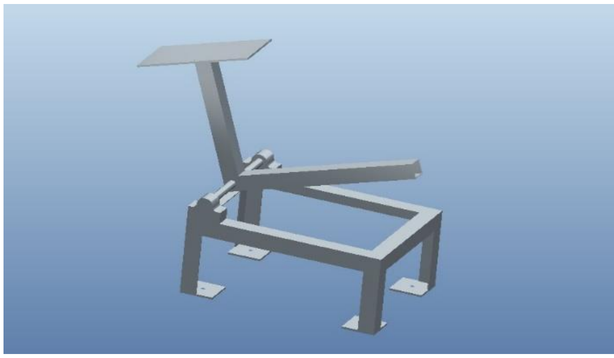


Figure 33: Demonstration model of a moment-arm based test stand

Another design concept, as seen in above figure, was considered for its simplistic yet effective design. This type of test stand is based on L-shaped design and has two moment arms, one vertical and the other horizontal. The point where the two arms meet is hinged via a pin-joint so that it can rotate about it. The engine is attached to the vertical arm such that its thrust force acts in the direction of the horizontal arm. This force produces a moment at the pin-joint which in turn causes the horizontal arm to rotate in the same direction as the vertical arm, particularly downward direction. At this point a load cell or a weighing scale is placed under the pin (fixed for single-point-contact between horizontal arm and scale) which gives off the value of force created by the downward push of the horizontal arm. It should be noted that the distance from the center of the engine to the pin-joint must be equal to the distance from the point of contact with the scale to pin-joint. In case, if the two moment arms are not equal in length, then the results shown by the weighing scale can be corrected by applying proportion. The advantage of using such a stand is that it allows a turbofan and turboprop to be mounted on it, making it practically more suitable for the experiment.



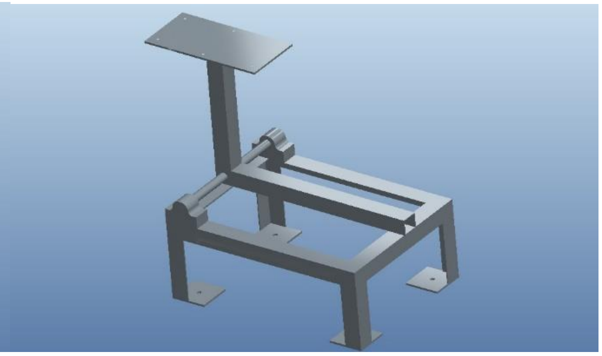


Figure 34: *CAD model of the test stand (a)*

Figure 35: *CAD model of the test stand (b)*

To construct a test stand for our turbofan engine, a 3D CAD model was built first for the illustration. The model was built by taking into consideration the dimensions of the engine and shroud. It was built slightly oversized, should it need to mount other turbofan engine with diameters up to 24 inches.

The base of the stand was constructed by 2x2 angle iron whereas the moment arms were made of 2x2 tubular iron sections. A metallic rod of 8mm diameter was welded where the two arms meet and was connected to the base via two journal bearings, one at each end. This allowed the moments arms to rotate about the pin joint as shown in figure 36.

Figure 36: *Base of the test stand showing the weighing scale*

The stand once constructed and mounted with the engine, was tested by applying 20Kg Load acting as thrust in forward direction at the center of the engine to check for the integrity of the stand. The test stand withheld the simulated thrust force and the weight of the engine and assembly which cumulates around 8Kg (weight of the engine + shroud + fan + other electronic accessories) easily without any deformation.

3.3 Experimental Setup

Figure 37: *Turbofan engine mounted on the test stand*

The experimental procedure involves running the engine at different throttle settings where thrust, fuel consumption in grams per second and RPM of the fan were recorded. The experiment was conducted such that at each throttle position, the engine was given 10 seconds to stabilize itself prior to taking the readings. Though the engine responds to the throttle settings quickly and stabilizes itself within 3 seconds, yet a stabilization time of 10 seconds was given. Once the engine RPMs stabilize, fuel mass in grams was noted. A 10 seconds time interval was given and at the end of this interval, fuel quantity was noted again. This gives off the fuel quantity used in grams per 10 seconds. At the end of each interval, the values of thrust, and RPMs of the fan were also noted. A 5 Kg fuel tank filled with diesel was placed on a weighing scale which measured the fuel quantity in grams with the minimum possible value of 0.5 grams measurement.

Figure 38: *Rear view of the engine*

3.3.1 Engine Run Test 1

The engine test run 1 was performed and the data was collected which is shown below in table 4.

The throttle was adjusted at an increment of 5% from 20% to 100% while 17% throttle position being the idle point. Fan RPMs were recorded, and the value of thrust was noted in grams. Fuel quantity was also noted in grams within an interval of 10 seconds.

The Value of Thrust Specific Fuel Consumption (TSFC) is calculated and is shown below in the table 4.

Measured Quantities					Calculated from Measured Quantities
Throttle	**Time Interval**	**Fan RPM**	**Thrust**	**Fuel consumed in 10 secs**	**Thrust Specific Fuel Consumption TSFC**
%	**Sec**	**rpm**	**(gm)**	**(gm)**	**(g/kN-s)**
17	10	1387	250	4	163.17
20	10	1689	380	4	107.35
25	10	1993	580	4.5	79.12
30	10	2384	760	4.5	60.38
35	10	2686	970	4.5	47.31
40	10	2913	1190	5.5	47.13
45	10	3245	1440	6	42.49
50	10	3596	1722	7	41.45
55	10	3883	2020	7.5	37.86
60	10	4191	2388	8	34.16
65	10	4479	2690	8.5	32.22
70	10	4774	3062	9.5	31.64
75	10	4988	3378	10.5	31.70
80	10	5263	3742	11	29.98
85	10	5468	4105	12.5	31.05
90	10	5681	4418	13	30.01
95	10	5779	4633	14.5	31.92
100	10	5888	4635	15	33.00

Table 4: *Engine Test Run 1*

The above table shows that at 17% throttle position, the engine was idling with fan rotating at 1387 rpms and producing very little thrust. During this idling condition, the engine consumed 4 grams of fuel in 10 seconds. At 50% throttle, the engine was producing around 1722 grams (16.89N) of thrust at 3596 fan rpms. The engine was consuming 7 grams of fuel in 10 seconds at 50% throttle.

At 100% throttle condition, the engine consumed 15 grams of fuel in 10 seconds while producing 4635 grams (45.45N) of thrust at 5888 fan rpms.

3.3.2 Engine Run Test 2

The engine test run 2 was performed similar to the test run 1 and the values were recorded which are shown below in the table 5.

Measured Quantities					**Calculated from Measured Quantities**
Throttle	**Time Interval**	**Fan RPM**	**Thrust**	**Fuel consumed in 10 secs**	**Thrust Specific Fuel Consumption TSFC**
%	**Sec**	**rpm**	**(gm)**	**(gm)**	**(g/kN-s)**
17	10	1403	260	4	156.89
20	10	1710	388	4	105.13
25	10	2057	573	4	71.19
30	10	2395	763	4.5	60.14
35	10	2705	973	5	52.40
40	10	2987	1180	5	43.21
45	10	3263	1145	6	42.34
50	10	3521	1718	6.5	38.58
55	10	3895	2016	7.5	37.94
60	10	4188	2388	8	34.16
65	10	4476	2689	9	34.13
70	10	4737	3062	9.5	31.64
75	10	4995	3379	10.5	31.69
80	10	5215	3742	11	29.98
85	10	5475	4102	12	29.83

90	10	5674	4421	13.5	31.14
95	10	5780	4632	14.5	31.92
100	10	5890	4636	15	33.00

Table 5: *Engine Test Run 2*

3.3.3 Engine Run Test 3

Again, similar to test run 1 and test run 2, test run 3 was performed with the values as shown in the table 6.

Measured Quantities					**Calculated from Measured Quantities**
Throttle	**Time Interval**	**Fan RPM**	**Thrust**	**Fuel consumed in 10 secs**	**Thrust Specific Fuel Consumption TSFC**
%	**Sec**		**(gm)**	**(gm)**	**(g/kN-s)**
17	10	1445	267	4	152.78
20	10	1742	390	4.5	117.67
25	10	2093	575	4.5	79.81
30	10	2411	769	4.5	59.68
35	10	2690	970	5	52.57
40	10	3006	1186	5.5	47.29
45	10	3309	1442	6	42.43
50	10	3513	1719	6.5	38.56
55	10	3899	2015	7	35.43
60	10	4153	2389	8.5	36.28
65	10	4475	2690	8.5	32.22
70	10	4753	3069	9.5	31.57
75	10	4939	3376	10	30.21
80	10	5273	3745	11.5	31.32

85	10	5480	4104	12	29.82
90	10	5684	4419	13	30.00
95	10	5775	4630	14	30.84
100	10	5889	4635	15	33.00

Table 6: *Engine Test Run 3*

4 RESULTS AND ANALYSIS

4.1 Thrust vs TSFC vs RPM

After collecting the data from the 3 test runs performed, the results that have been gathered are analyzed in this section. Thrust, Thrust Specific Fuel Consumption (TSFC) and Fan RPMs are recorded and presented in tabular and graphical form.

Three different tests were performed to validate the accuracy of the results.

4.1.1 Throttle vs RPMs

In this section, the throttle vs rpm of the fan and engine core are studied. The fan and the engine core rpm (rpm of the compressor and turbine shaft) are noted at different throttle settings. The following table shows the values noted at each throttle point.

	Fan RPMs			**Core RPMs**		
Throttle	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**
17%	1387	1403	1445	54252	54397	54421
20%	1689	1710	1742	59903	60113	59990
25%	1993	2057	2093	66231	65890	66158
30%	2384	2395	2411	71870	71394	71745
35%	2686	2705	2690	77884	77305	77558
40%	2913	2987	3006	83910	83715	83368
45%	3245	3263	3309	89340	88800	88913
50%	3596	3521	3513	95794	95990	96009

55%	3883	3895	3899	101555	101873	101449
60%	4191	4188	4153	107683	106906	107205
65%	4479	4476	4475	113968	114116	113989
70%	4774	4737	4753	119870	119913	122081
75%	4988	4995	4939	125194	125994	125685
80%	5263	5215	5273	131686	131888	132019
85%	5468	5475	5480	137885	137998	138129
90%	5681	5674	5684	143679	143893	144095
95%	5779	5780	5775	149156	149355	149559
100%	5888	5890	5889	153531	152880	152342

Table 7: *Throttle vs RPMs*

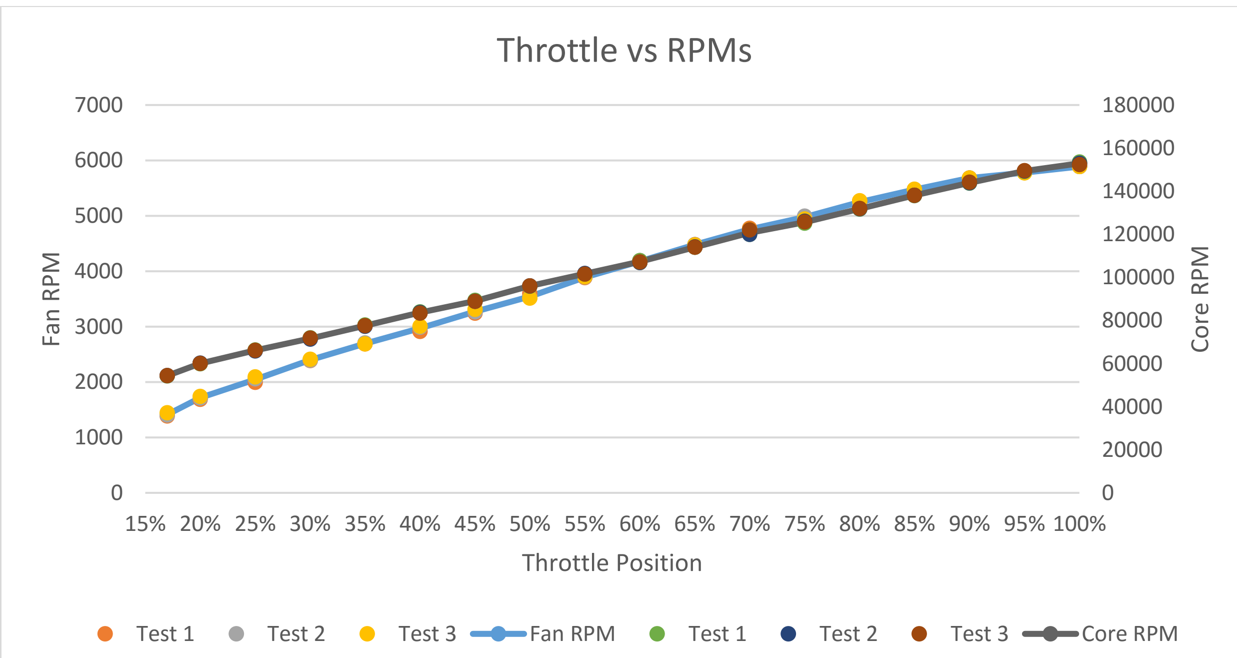


Figure 39: *Graph showing the Throttle vs RPMs curves*

The above graph is generated from the table 7 to analyze the trend of the rpm against the throttle. The relation between the rpm of the fan and the core is almost linear with respect to throttle settings. However, at around 85% throttle, the rpm of the fan started struggling to elevate more. One particular reason for this is that the fan that is used has a rated rpm of 5500. The above graph also shows that after 5500 rpm, the fan does not accelerate as it did earlier.

It is interesting to note that the earlier turbofan engines have the fan mounted on the same shaft at which the compressor and turbines are mounted and thus have the same rotational speed. While modern turbofan engines incorporate a gearbox between the fan and the main shaft which rotates the fan and the compressor/turbine at different speeds. However, this gear ratio is fixed, meaning that at different throttle settings, the fan would rotate at a fixed gear ratio to the main shaft.

While our turbofan engine has the fan mounted on the secondary shaft which has no physical connection to the main shaft. The two independent shafts allow the fan and the core to work independently at variable gear ratios throughout the entire throttle settings.

As can be observed in the above graph, the fan rpms were independent to the rpm of the core and thus were more dependent on the design of the fan rather than the limitations imposed by the core. Had the fan been more aerodynamically efficient or had a rated rpm of 7000 instead of 5500, the fan would have reached higher speeds.

4.1.2 Fan RPMs vs Thrust

The following table shows the values noted for thrust against their corresponding fan rpms in the 3 different tests performed.

Test 1		**Test 2**		**Test 3**	
Fan RPMs	**Thrust (N)**	**Fan RPMs**	**Thrust (N)**	**Fan RPMs**	**Thrust (N)**
1387	2.45	1403	2.55	1445	2.62
1689	3.73	1710	3.80	1742	3.82
1993	5.69	2057	5.62	2093	5.64
2384	7.45	2395	7.48	2411	7.54
2686	9.51	2705	9.54	2690	9.51
2913	11.67	2987	11.57	3006	11.63

3245	14.12	3263	14.17	3309	14.14
3596	16.89	3521	16.85	3513	16.86
3883	19.81	3895	19.77	3899	19.76
4191	23.42	4188	23.42	4153	23.43
4479	26.38	4476	26.37	4475	26.38
4774	30.03	4737	30.03	4753	30.09
4988	33.12	4995	33.13	4939	33.11
5263	36.69	5215	36.69	5273	36.72
5468	40.25	5475	40.22	5480	40.24
5681	43.32	5674	43.35	5684	43.33
5779	45.43	5780	45.42	5775	45.40
5888	45.45	5890	45.46	5889	45.45

Table 8: *Fan RPM vs Thrust*

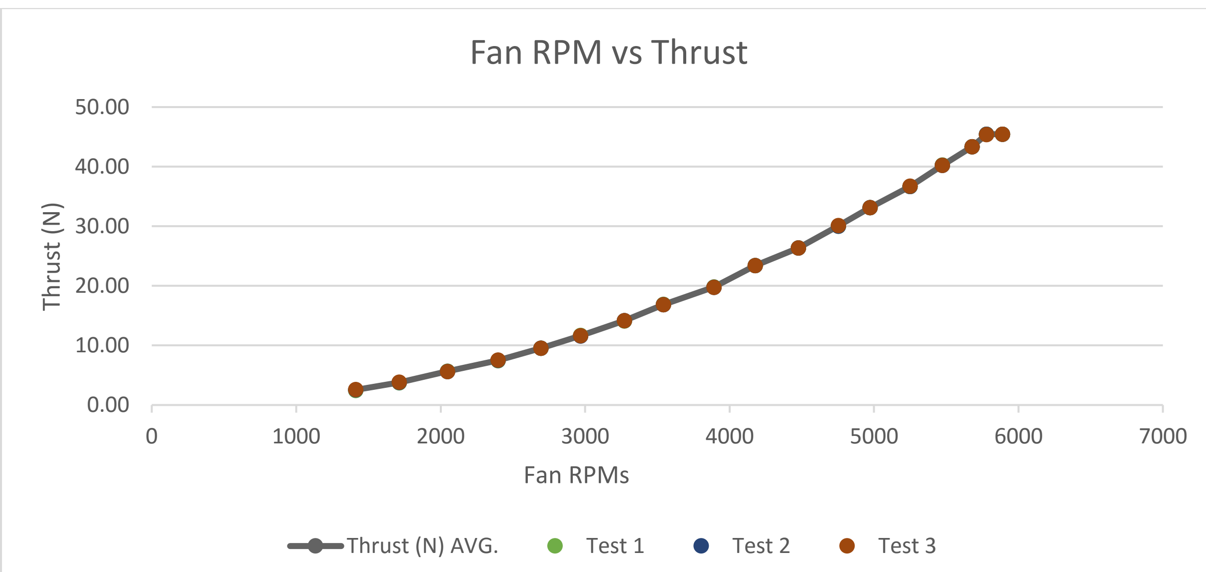


Figure 40: *Graph showing the Thrust against the fan RPMs*

The above graph is generated from table 8 and shows the trend line for the thrust against the fan rpms. The thrust increases exponentially with the increase in rpms however at nearly 5800 rpms, it maxed out. This can be justified since we know that the fan was unable to accelerate more from 95% throttle to 100% throttle and thus had the thrust limited with respect to rpms.

4.1.3 Thrust vs TSFC

This section discusses the Thrust Specific Fuel Consumption (TSFC) with respect to the thrust produced. The following table shows the values of TSFC calculated against the thrust for each test.

Test 1		**Test 2**		**Test 3**	
Thrust (N)	**TSFC (g/kN-s)**	**Thrust (N)**	**TSFC (g/kN-s)**	**Thrust (N)**	**TSFC (g/kN-s)**
2.45	163.17	2.55	156.89	2.62	152.78
3.73	107.35	3.80	105.13	3.82	117.67
5.69	79.12	5.62	71.19	5.64	79.81
7.45	60.38	7.48	60.14	7.54	59.68
9.51	47.31	9.54	52.40	9.51	52.57
11.67	47.13	11.57	43.21	11.63	47.29
14.12	42.49	14.17	42.34	14.14	42.43
16.89	41.45	16.85	38.58	16.86	38.56
19.81	37.86	19.77	37.94	19.76	35.43
23.42	34.16	23.42	34.16	23.43	36.28
26.38	32.22	26.37	34.13	26.38	32.22
30.03	31.64	30.03	31.64	30.09	31.57
33.12	31.70	33.13	31.69	33.11	30.21
36.69	29.98	36.69	29.98	36.72	31.32
40.25	31.05	40.22	29.83	40.24	29.82
43.32	30.01	43.35	31.14	43.33	30.00
45.43	31.92	45.42	31.92	45.40	30.84
45.45	33.00	45.46	33.00	45.45	33.00

Table 9: *Thrust vs TSFC*

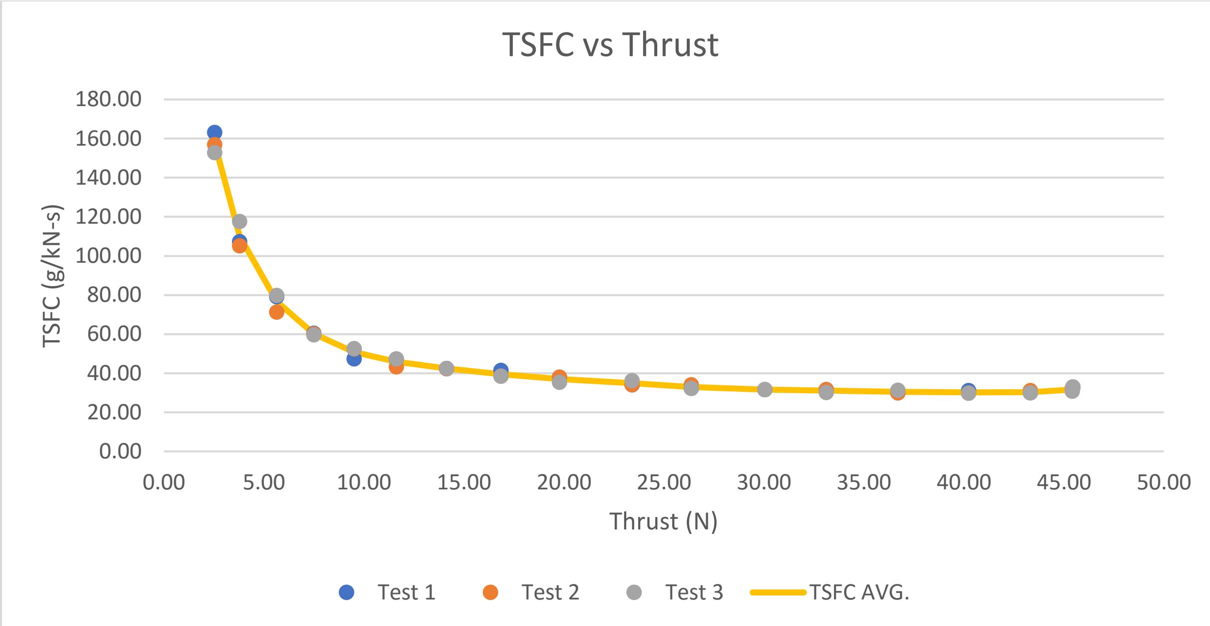


Figure 41: *Graph showing the TSFC plotted against the thrust*

The graph in figure 41 is obtained from table 9. It shows the trend followed by the TSFC with respect to thrust. With an increase in thrust, the TSFC starts to decrease rapidly till around 10N (35% throttle), from there it starts to straighten out. Increasing the throttle from 95% to 100% only increased the thrust with very little amount thus causing the TSFC to rise slightly.

The TSFC could have been much lower, had the fan been more efficient or rated to operate at 7000 rpms. It is wise to operate the engine at nearly maximum throttle since it consumes the least amount of fuel for the thrust it produces. This has been the case for almost all jet engines where they have the lowest TSFC from 80% to 100% throttle, particularly because the gas turbine engines are designed to be operated and cruise at nearly maximum power during the flight. This makes the gas turbine engines much powerful for their size (high power to weight ratio) as compared to reciprocating engines, making them suitable for aircrafts.

4.2 Thrust Specific Fuel Consumption comparison with K60 Turbojet

In this section, a brief comparison of our turbofan is done with a turbojet of the same size.

The engine used in this experiment is a KingTech K60-TP which is basically a KingTech K60 Turbojet coupled with a secondary turbine and a gearbox. The K60 turbojet has been modified into a turbofan with the addition of a secondary turbine, gearbox and a fan. The use of the gearbox allows bigger fan to be used at reduced rpms.

The comparison is done between a KinTech K60 Turbojet and our custom-made Turbofan (K60 TJ+gearbox+fan) in such a way that the values have been considered at maximum throttle. Since, we have the data available for the turbofan for entire throttle setting however, we do not have the data for the turbojet for entire throttle settings, as it would require us to purchase a separate turbojet engine which is, at the moment, limited by the cost incursion. Therefore, we took the data for the K60 Turbojet for maximum throttle from the KingTech's Engine Manual book.

At max throttle	K60 Turbojet	K60 Turbofan
Thrust (N)	60	45
Fuel Consumption (gm/min)	195	90
Fuel Consumption (gm/s)	3.25	1.5
TSFC (gm/(kN-S)	54.17	33.33

Table 10: *comparison between K60 Turbojet and K60 Turbofan*

The above table 10 shows that at maximum throttle the K60 Turbojet produces 60N of thrust while consuming 195 grams of fuel per minute giving a TSFC value of 54.17 gm/(kN-S). Whereas, our Turbofan engine produced 45N of thrust while consuming 90 grams of fuel per minute giving a TSFC value of 33.33 gm/(kN-S). This indicates that our turbofan engine's TSFC is 38.47% lower than the K60 Turbojet.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The results of the experiments indicated that a turbofan engine is more economical to operate than a turbojet of the comparable size. The turbojet engine releases a gush of hot gases into the atmosphere wasting much of the energy from the system as heat. On the other hand, a turbofan uses additional turbines that harness the energy from exhaust gases which then drive a fan that produces thrust. This experiment shows that our turbofan engine had a TSFC 38.47 lower than the turbojet of the same size. In the case of larger turbofan engines used in the commercial airliners, the TSFC is even more significantly lower.

The micro-turbine engines use a single stage centrifugal compressor and a single stage turbine whereas the large commercial turbofan engine have up to 17 stages of axial compressors and 8 stages of turbines, giving more pressure ratios and overall higher efficiency than a micro-sized turbine engine.

The use of independent shafts allows the fan to operate at its optimal speed while the compressor and the turbine can operate at their optimal speeds, at variable gear-ratios at different power settings.

5.2 Future Recommendation

This research was carried out to find out the whether a mini-turbofan engine would be more economical to develop and operate than a turbojet or not, as is the case in case of larger commercial jet engines. The results of the experiment came out to be positive, opening a gateway for further research and development.

Following are the points that can be considered for further development and enhancements to the turbofan engine's performance:

- Use different fans and study the effects on thrust and TSFC.
- Design a fan specifically for the engine and study its performance.
- Attempts be made to increase the thrust by increasing fan RPMs in order to lower the TSFC.
- A complete thrust and TSFC curve be obtained of a K60 Turbojet for the comparison with the turbofan engine.
- Study the effects on thrust and TSFC with a variable pitch fan.

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