"Turbocharger/Heat Exchanger Concept"

Abstract

Turbochargers are an ever more popular technology which utilises the hot exhaust gases emitted from an engine to force fresh air into the cylinders of the engine to help in producing more power. In this process heat is transferred to the turbo and in some cases the turbo becomes extremely hot. This heat which is otherwise wasted can be conducted through the components of the turbocharger and heat the incoming fresh air which ideally we need to stay cool.

To combat the heat transfer the two halves of the turbo could be moved apart but then the shaft would be prone to twisting the shaft. The shaft would have its diameter increased, and made hollow. This paper looks at the feasibility of running water/coolant through the hollow shaft to keep the compressor side of the turbo cool and whether it could be made into a practical solution for future turbocharging solutions.
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Introduction

In today's society, there is a massive push for renewable energy, energy conservation and for motor cars to be 'greener' i.e. more environmentally friendly. This would involve better use of energy and energy recovery devices as can be seen with the likes of KERS, Kinetic Energy Recovery System in Formula 1 currently. The turbo/heat exchanger concept being proposed would help recover some of the heat energy from the turbo which otherwise would have been discharged through the exhaust into the atmosphere. What this is then used for is beyond the scope of the project but it could be anything from the heat being radiated remotely or as extreme as pre-heating water for hydrogen generation.

The concept is relatively simple. It is a self pumping heat exchanger completely housed within the turbo and turbo shaft. The two halves of the turbocharger (turbine & compressor) are moved apart to hinder heat transfer between them and water/coolant is passed through the centre of the now hollow turbine shaft. The shaft needs to be a larger diameter and hollow to cope with the torsional effects caused by the longer shaft. To provide the self-pumping aspect, the shaft will have an Archimedes screw through it to cause the pressure difference in the shaft that will draw water in one end and eject it from the other. These concepts will be shown in more detail later.
Scope and Objectives of Project

This project, for all the content, variables and iterations that will come with it will need to have a particular Scope and targets applied to it so that the Outcomes can be defined and the proverbial tail is not being chased. These are as follows:

Aims of Project

- Establish an understanding of the theory forced induction.
- Investigate the methods, systems and components required.
- Construct a CAD model of Turbo Concept
- Perform Calculations for Turbo Parameters
- Evaluate Performance
- Evaluate Future of Concept
- Draw Conclusions

Aspects Beyond the Scope

- Engine Specification - *One will be selected to get example numbers from but there will be no focus on improving the engine aspect of the system.*
- Engine Performance - *As mentioned above, the only aspect the engine will be used for is to get relative temperatures and pressures for the Turbo.*
- Applications of Heated Water from Turbo - *There are many applications for this but this project is just to demonstrate the concept and investigate its feasibility.*
- Exact Turbine and Compressor Blade Modelling - *This would be another whole project on its own as demonstrated in "Design Of An Integrated Turbocharger" (See Literature Review)*
- Final Design Dimensions - *As this is evaluating the concept there will be no final design constraints placed on turbo other than fundamental operating principles.*

Anticipated Outcomes

- An understanding of how the Turbo/Heat Exchanger Concept will operate.
- A Conclusive Evaluation on the Feasibility of the Concept Working
- A Speculative Insight into the Potential Future of the Concept

Relevant Background Knowledge

Modules covered in University which aid with Background Knowledge of the issue include:

- Aerodynamic & Thermal Management
- Engine & Drivetrain Design
- Mechanical & Thermal Design
- Race Engineering
- Design, Prototyping & Testing
- Motorsport Control Systems
Background Information

Before the Concept can be investigated or analysed we firstly need to look at the principles that will affect its performance and specification otherwise it would really be taking a shot in the dark.

Four Stroke Engine Theory

To get to grips with the Four Stroke Engine we first of all need to understand what is happening during engine operation.

The Basic Four-Stroke Cycle

As the name suggests, there are four stages to the Four Stroke Engine operation:

a) Induction Stroke
b) Compression Stroke
c) Power Stroke
d) Exhaust Stroke

These are shown below:

Figure 2 above shows the four strokes that occur per cylinder in every two revolutions of the crankshaft. Each stroke is 180° of crank rotation. On the Intake Stroke, as the piston is at TDC (Top Dead Centre) the piston starts to move down the cylinder due to clockwise rotation at the crankshaft. At the same time the inlet valve opens allowing an air/fuel mixture to fill the void being created by the piston’s downward movement. Just after the piston reaches BDC, the inlet valve shuts sealing the cylinder. The Compression Stroke then takes place. As the crankshaft keeps rotating clockwise, this makes the piston rise up and compress the fuel/air mixture trapped in the top of the cylinder. This increases the pressure by the 'Compression Ratio' then near TDC, the spark plug ignites
the pressurised mixture. The Power Stroke now occurs as the fuel uses the oxygen in the air to combust. This combustion increases the pressure within the cylinder which forces the piston down hence providing torque to the crankshaft. Once the piston is near BDC again, the Exhaust Valve opens, and as the piston returns to TDC the used Exhaust Gas is pushed out the cylinder into, in our case the Turbocharger. Near TDC the Exhaust Valve shuts and the Inlet Valve opens for the whole process to start again.

There is obviously only one stroke providing energy into the system so multiple cylinders are used to smooth the process. In a four cylinder engine there is always one cylinder on a power stroke as the phase difference between each cylinder is 90°.

This is just a basic description of a four stroke as obviously there are numerous performance tweaks that can be applied to manipulate this cycle to get the most out of it.

**Air Density**

A critical aspect of Engine Performance that needs to be understood and considered is Air Density. The Engine makes its output Torque by pressurised combustion of Petrol with Air. As petrol is the aspect that provides the energy in the reaction, we want as much of it in the cylinder as possible.

However, this is no good unless we mix it with the correct ratio of air. The Stoichiometric Ratio is regarded as the optimum Air/Fuel ratio in steady state conditions at 13.5:1. This Ratio may be changed by the ECU fitted to the engine depending on working conditions.

So to get as much fuel into the cylinder as possible whilst keeping the Air/Fuel Ratio as constant as possible, the only solution is to get more air into the cylinder. The cylinder of a Naturally Aspirated engine will draw in air on the downwards movement on the induction stroke. This will, in an ideal world, fill the cylinder 100% full of air/fuel but in practice:

"unsupercharged engines seldom, if ever, attain a volumetric efficiency of 100%"

A. Graham Bell (Four Stroke Performance Tuning, p64)

This leaves us with two main options for improving the amount of air in the cylinder. Option 1 is to keep as much density in the air as possible thus there would be more air molecules in the same volume or Option 2: Forced Induction.

We’ll look at the Forced Induction route later but briefly for now, to get more density (or lose less density as such) the induction system needs to be optimised to predominantly keep the air flow cool and reduce pressure loss because as temperature increases the density decreases. Cold-Air-Feels, Sports Air Filters, Throttle Bodies and good head/throttle/manifold design all contribute towards this. Another aspect that needs to be considered is Altitude. As can be seen in Figure 3, Air density decreases as the Altitude increases which means that there will be effectively less air molecules in the cylinder and hence less fuel.

"In fact, a rule of thumb is that hp will decrease 3% for each 1000ft"

A. Graham Bell (Forced Induction Performance Tuning, p62)
Fuel
Here in the United Kingdom, petrol can be purchased in two variants on forecourts: 97RON unleaded and 99RON Super Unleaded. The RON number or Research Octane Number basically determines how much energy is needed to combust the fuel. Because a higher RON fuel requires more energy it will not be as susceptible to knock or pre-ignition which means the engine can run more Advance and hence the Power Stroke can effectively be longer or more sustained meaning more power. As an example, Ginetta G50/55s race in the UK using 102 RON Fuel for this very purpose, however they are mapped to run on 99 RON so testing can be more cost effective.

Engine Efficiency
There are several aspects to a petrol engines efficiency. These range from throttle plate diameter right to the fuel injection timings. The engine is at its most efficient when all the various systems are at their optimum. A simple engine efficiency that forced induction may resolve is the Volumetric Efficiency. This is a percentage of how full the cylinders are of air compared to their maximum and it varies constantly. Optimus is 100% and as mentioned earlier it’s rare to find a N/A engine with 100%. Some racing engines will get close but to improve this efficiency, forced induction can increase it dramatically, in some cases over 300% in the old Turbo F1 cars.
**Forced Induction Theory**

Forced Induction is a method of increasing Power and Efficiency in an internal combustion engine by effectively giving the induction side of the engine a positive pressure which means the air/fuel mixture fills the cylinder more effectively than N/A or gives even more than 100% VE.

**Why Forced Induction?**
There are two key reasons for applying forced induction to a four stroke petrol engine:

1. **Performance** - As previously described, forced induction gives the option of increasing performance by cramming more air into the cylinder’s with more fuel to give more torque/power.

2. **Economy** - Due to the aforementioned performance potential gains and better efficiencies, there can be a downsize of engine whilst still getting the performance of a bigger engine. Done correctly the downsized engine will get the economy of a smaller engine and not lose any performance over the previously bigger equivalent powered engine.

A very typical application of the economy aspect is being implemented by the FIA in international motorsport current where to cut costs and promote a 'greener' image, numerous different racing series/categories are switching to the 'Super 2000’ rule which means cars are now moving to 1.6 litre four cylinder turbocharged engines. The difference between each series is the boost pressure. This means there is one design of engine to manufacture and since the turbo boost variation is in place it means the hierarchy of performance is maintained thus matching performance and cutting costs. The smaller engines are also more economical but only a small amount due to the nature of the driving i.e. WOT for most of the time.

![Schematic of How the Turbo Works. Blue is intake airflow, red is exhausted flow](image)

*Figure 4: Schematic of How the Turbo Works. Blue is intake airflow, red is exhausted flow*
Figure 5: Turbocharger Or Supercharger? There has always been a long running argument over which is best.iii

**Forced Induction Methods**

There are fundamentally two methods of forced induction. Superchargers and Turbochargers. The main difference being that a supercharger is driven off a mechanism whereas the Turbocharger is driven by rotation of a turbine in the path of an engine’s exhaust gases. In Figure 5, the Big Turbo can be seen on the left, a small turbo on the right and a supercharger in the centre. As mentioned the supercharger is driven by a mechanism although in automotive application this is most often the engine crankshaft itself. There are some that are spun using an electric motor. Both have their pros and cons but fundamentally work in the same way. The turbochargers have two main parts to them, the turbine and the compressor. The two are connected to the opposite ends of a shaft and as the exhaust gases pass through the turbine and produces torque for the shaft the compressor obviously has to turn at the same rate. As the Compressor wheel turns the atmospheric air is drawn in and pressurised towards the intake manifold. More often than not an intercooler will be in place between the compressor exit and the inlet manifold.

The argument: Superchargers do not suffer from lag so generate boost straight away and spin at rate that is directly proportional to the engine revs. They do not need a wastegate but could do with an intercooler to cool the compressed air but this would not be practical. Turbos are slightly more efficient due to the fact they are driven by 'discharged energy' in the exhaust. By this we mean the exhaust gases that spin the turbine have left the engine and would not have contributed to the process otherwise so the turbo is effectively salvaging power from nothing. That said the turbo does suffer lag as it always has to 'catch-up' with the engine. Because the engine's exhaust gases power the turbo, the engine needs to start revving before the turbo can actually produce enough boost to overcome what the engine was drawing in by itself. Properties that affect Turbo-Lag are turbo sizing, turbo inertia and engine load. A turbo that is too big for the engine its connected to will suffer a lot of lag even if there is potentially big power in high rpm. The mass of rotating components in the turbo will cause there to be some kind of inertia (resistance to change in motion) which will delay spool-up time if not as light as possible. Also the engine load can affect turbo-lag. If the driver does not give the engine some revs and short-shifts between gears then lag can be very evident as the low revs means a low amount of exhaust gas energy/velocity.

**Turbocharger Applications**

Turbochargers can be used in many different applications. The WRC car below in Figure 6 is a good example of one end of the spectrum.
This end of the spectrum is where the turbo needs to be relatively compact, super strong and lightweight with a high output and strong anti-lag systems applied. The other end of the spectrum would be something like marine diesel turbos as seen in Figure 7.

Marine Diesel Turbos can be massive. The turbo in Figure 7 will be at least a metre in diameter which when compared to the turbo on something like a diesel city car is a massive difference. The amount of air the marine engine will flow will be very high due to the sheer size of the entire unit but because the engines will most likely run at constant speeds and lower rpm there is not such a concern about turbo-lag or too high temperatures etc.

**Turbocharger Development**

Turbos have come a long way in the last 100 or so years. There were a few key events that really drove the development of turbos from being hideously crude systems to the modern systems we know and almost forget about due to their supreme refinement. The first quarter of the 20th century saw the introduction of turbos and some developments but between then and World War 2 turbos were being developed for fighter aircraft. This started out just for diesels as their exhaust temperatures are generally lower than petrol engines, but as development in materials continued turbos became capable of handling much higher temperatures (approx 800°C).
The turbocharged petrol engined 'Flying Fortress' and 'Thunderbolt' aircraft were an example for the potential of turbocharging. However as the implementation and development of jet turbine engines started to increase experts predicted the end for the piston engine which would have effectively ruled out the use of turbos. The experts couldn’t have been more wrong. The piston engine became more refined as a better understanding of its workings came about and the next big leap for turbochargers as we know them today came from Formula 1 and Rallying. In the late 70's and early to mid eighties the turbocharger was developed and came to dominate Formula 1 in the late eighties. Several manufacturers got in on the act including Alfa Romeo, Ferrari, Renault and TAG Porsche (See Figure 8). These Formula one engines had all various tricks with the turbo technology and anti-lag which meant that in qualifying trim some units could produce in excess of 1250hp. It is rumoured that there was a engine capable of 1500 horsepower in qualifying trim but the teams dynamometer couldn’t read higher than 1280hp so it was a guess by the team's engineers. This figure got pegged back further and further as the permitted boost was restricted, then the fuel usage was restricted when F1 teams started working out ways around the restrictions with clever 'anti-lag' systems.

In rallying, SAAB were pioneering the turbo technology and with moderate success applying it to their road vehicles. However in the 'Group B' era of rallying several manufacturers again fought for supremacy using brutal turbocharged beasts such as the Audi Quattro, Ford RS200, Lancia Delta S4, Peugeot 205 Evo II and the Renault 5 Turbo.
In both scenarios of F1 and rallying speeds were dangerously high. The FIA kept implementing tougher regulations on turbocharging including restricting the size of the turbo inlet. Eventually Formula 1 ditched turbos altogether and are only just rethinking the concept whereas Group B rallying was replaced with Group N which saw cars at a much closer looking spec to road cars and a horsepower limit of 300bhp. Again recently the WRC has also moved towards the super2000 rules with smaller turbocharged engines for economy and cost reasons.

![Audi Sport Quattro with almost 600bhp](image)

**Figure 10: Audi Sport Quattro with almost 600bhp**

All this development within motorsport has meant however that today's modern road cars have exceptional behaviour with respect to drivability and response in turbos. This is helped a lot by modern control systems such as fuel injection, variable vane/nozzle technology within the turbos and a better understanding of running multiple/hybrid turbos.

**Turbocharger Specifications**

Turbochargers are usually either made in-house by car manufacturers or by external companies such as Garrett or KKK. Quite often car manufacturers will use turbos from other car manufacturers such as Mitsubishi to help cut development costs.

All this means there are an awful lot of turbo setups available on the market. The compressor wheel/housings need specifying along with the turbine wheel/housings too. These are specified with 'Maps' that are matched for Pressure Ratios and Airflow.

To try and get a grasp of what temperatures and pressures a typical turbo will produce one will be selected to work with an engine that has plenty of data available for it as detailed later in the Calculations section.
Heat Exchanging Theory

A heat exchanger, is a device used to effectively transfer heat from one fluid to another whether it be through a wall or direct contact. Heat exchangers are available in a massive range of shapes and sizes and are used in refrigeration, air conditioning, internal combustion engines, space heating etc.

Why Heat Exchangers?
Heat exchangers are essential for tasks such as regulating a car engine temperature or keeping a fridge cool. They perform tasks that previously would have meant things being air-cooled or more crudely performed. An example of such is an induction heater, the metal element has a current passed through it to which it then heats up and air is passed over it to warm the air. Previously this task would need to rely on radiated or convective heat by means of a fire etc.

Types of Heat Exchanger
As mentioned there are several different applications for heat exchangers so it seems fair that there are numerous different types of exchanger too.

These include the different combination of materials e.g. Metal - Metal, Metal - Air, Metal - Water/coolant etc. In a car there are several heat exchangers. The engine has coolant running through it so is a metal - coolant type which then goes the radiator which is a coolant - metal - air cross flow type. The cabin heater gains its heat from an exchanger under the dash which is water - metal - air. The exhaust system is effectively a gas-metal-air exchanger. The power-steering, air conditioning, brakes, turbo etc are all effectively heat exchangers that are used to regulate some aspect of each device.

Figure 11: Intercoolers are usually an Air-to-Air cross flow exchanger but some Air-Water performance ones exist.

Figure 11 is an extreme example of an intercooler setup with twin exchangers either side of the radiator. Both the radiator and intercooler are examples of cross flow heat exchange but there is also parallel flow and counter flow exchangers available. In a parallel exchanger the two fluids running in the same direction and a counter flow runs in the opposite direction.

This will become something potentially worth investigating in the turbo concept in the next section.
The Concept

As described in the introduction, the concept is a turbocharger with a relatively large diameter hollow shaft that draws coolant through it by means of an Archimedes screw within the shaft. The screw provides a pressure differential between the inlet and outlet which acts as the pumping system.

Figure 12: Fully Assembled view of Concept turbocharger as modelled in ProEngineer.

Overview

As can be seen in Figure 12 and Figure 13, the concept visibly looks like a turbo but with a couple more apertures sprouting from it. This isn’t too far from what the concept is actually. The apertures are the coolant supply and exhaust pipes. They are integral to the water jackets that surround the shaft at either end. The top one passes water into the shaft at the cold end, the Archimedes screw draws the coolant through the shaft from the cool compressor side to the hot exhaust side and the positive pressure along with centrifugal force forces the coolant out the end of the shaft into the lower water jacket. Three large ball bearings carry the shaft and allow it to spin freely. These are lubricated by an oil system similar to a regular turbo.
Component Detail

To get an even better grasp of the concept, here is some detail about the major components.

Shaft
The shaft is effectively a hollow tube supported by three ball bearings and has a helical screw inside it. Each end of the shaft has either the compressor or turbine blades, the latter providing the torque to rotate the system. As the shaft rotates and the screw turns, there is a pressure shift - increased towards the hot exit end and similar and decreased on the input side. This pressure difference and the screw physically pushing the fluid by shear forces is what provides the flow to the system. If the system starts to turn there will admittedly be relatively high inertia forces to overcome and due to this the turbo/throttle response may suffer. However, as the system is at a much lower temperature than a conventional turbo there is less chance of temperature fatigue.

As can be seen in Figure 14, the shaft has the holes for transferring water in/out at either end. These holes open up approximately 2/3 of the shaft’s water jacket surface area to the flow. The inside edges are tapered as to aid the fluid movement by a scissor like shearing action at the outer surface of the shaft. It allows less resistance to the flow of the water by allowing it to flow naturally to the
outer parts of the shaft's inner radius rather than being forced into the shaft which would make the fluid naturally try to flow into the centre of the shaft and would cause a lot more drag resistance.

Figure 14: The concept shaft. The blades either end are visible along with holes for the water jackets.

As can also be seen in Figure 14, the water jackets opening has a high side edge. This is where the seal would be, but as the engineering tolerances between the water jacket and the space on the shaft are so small anyways the sealing of the water jackets has not been greatly investigated. Another logic with this was that if the concept doesn’t work then there has been no wasted time fiddling with small tasks like seals.

Figure 15: This shows how the shaft sits within the entire assembly

**Shaft Screw**

As can be seen in Figure 15, the shaft’s screw passes through the shaft between the inner edge of each water jacket. As will be seen in the calculations section the screw could be adjusted
dimensionally to rev higher or have a bigger flow area depending on the application. Figure 15’s screw has a 15mm pitch and extends all the way to the rotating centre axis. Other design ideas that could be investigated in future is partial screws i.e. no screw down the centre axis of the shaft - just at the outer walls. This could potentially lead to less resistance and less likelihood of cavitations in the fluid.

![Figure 15: The water jackets are actually pretty simple and clamp over the shaft.](image)

**Water Jackets**

As shown in Figure 16, there isn’t much to the water jackets. They each comprise of a tube which runs into an elbow where the cross sectional area changes from a circle to a rectangle. This allows the fluid to effectively surround a larger area of the shaft which should assist the shaft to draw in and expel coolant. As the nature of this project is to prove/disprove the concept, the dimensions of these jackets is variable. For example if there were a cavitation issue in the jacket, either of the flow areas (pipe leading in/out or the shaft surround area) could be enlarged - probably in the width and the shaft would need to be modified also. The jacket retainer simply bolts onto the actual water jacket in a similar fashion to a big end on a crankshaft.

![Figure 16: Water jackets are actually pretty simple and clamp over the shaft.](image)

**Figure 17: The space for the water jackets is left in the casing. Also visible is the holes in the shaft for drawing/expelling the coolant.**
Other Components

The other components in the turbo/heat exchanger concept include the bearings, casings and blade housings. These have all been modelled in ProEngineer as can be seen in the Assembly pictures but are really only for display purposes as they would need to be specified for a particular application.

Figure 18: Various Views showing the casings, blade housings and bearings.
Calculations

This is the section where it counts. The concept is very believable even to expert eyes but will it actually work. This section explains the calculation steps to try and aid this decision. Each section of the entire Engine system needs to be analysed so as to get realistic numbers to input into the turbo.

Engine

We start with the engine. Initially this was going to be a generic 2 litre turbo engine but as is a very useful thing to have is real life information about an actual real turbo engine and written data.

With this decision made it was decided that due to availability the engine used in the calculations would be a Volvo B5234T engine found in the classic Volvo V70 T5. This car was defined as the ultimate combination of turbocharged speed and Volvo estate practicality, so much so, pretty much every police force in the UK still uses Volvo V70s even if they have moved from the T5 petrol to the D5 diesel engines. The engine is a 2.3 litre, 20 valve, 5 cylinder engine which is turbocharged with a proper turbo so as standard they deliver 240bhp at 5200rpm and a peak torque of 330Nm at 2400-5200 rpm.

So we begin by inputting the appropriate values into a spreadsheet.

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<td>Stroke</td>
<td>3500 KJ/kg</td>
</tr>
<tr>
<td>Valve Lift</td>
<td>Fuel Density</td>
</tr>
<tr>
<td>Cylinder</td>
<td>719 kg/m³</td>
</tr>
<tr>
<td>Spindle Diameter</td>
<td>Coolant Density</td>
</tr>
<tr>
<td>Fuel Rail Pressure</td>
<td>1113.2 kg/m³</td>
</tr>
<tr>
<td>Fuel Pump Supply Rate</td>
<td>Coolant Temp</td>
</tr>
<tr>
<td>Fuel Return Rate</td>
<td>17 °C</td>
</tr>
<tr>
<td>Fuel Pump Return Rate</td>
<td>Water Density @20°</td>
</tr>
<tr>
<td>Fuel Rail Pressure</td>
<td>998.207 kg/m³</td>
</tr>
<tr>
<td>Fuel Pump Supply Rate</td>
<td></td>
</tr>
<tr>
<td>Fuel Return Rate</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail Pressure</td>
<td></td>
</tr>
<tr>
<td>Fuel Pump Supply Rate</td>
<td></td>
</tr>
<tr>
<td>Fuel Return Rate</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail Pressure</td>
<td></td>
</tr>
<tr>
<td>Fuel Pump Supply Rate</td>
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<td>Fuel Return Rate</td>
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<td>Fuel Rail Pressure</td>
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<td>Fuel Pump Supply Rate</td>
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<td>Fuel Return Rate</td>
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<td>Fuel Rail Pressure</td>
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<td>Fuel Pump Supply Rate</td>
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<td>Fuel Return Rate</td>
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<tr>
<td>Fuel Rail Pressure</td>
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<tr>
<td>Fuel Pump Supply Rate</td>
<td></td>
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<td>Fuel Return Rate</td>
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<tr>
<td>Fuel Rail Pressure</td>
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<tr>
<td>Fuel Pump Supply Rate</td>
<td></td>
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<tr>
<td>Fuel Return Rate</td>
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<tr>
<td>Fuel Rail Pressure</td>
<td></td>
</tr>
<tr>
<td>Fuel Pump Supply Rate</td>
<td></td>
</tr>
<tr>
<td>Fuel Return Rate</td>
<td></td>
</tr>
<tr>
<td>Fuel Rail Pressure</td>
<td></td>
</tr>
</tbody>
</table>

Figure 19: Summary of Spreadsheet Input Data

These figures can now be altered in this summary page and the outputs change automatically when we're done, however this is going to be a simplified engine model as there would be a lot of advanced CFD work and mapping that would need to happen to make an accurate model.

Also, a turbo engine is effectively an iterative process to work out temperatures and pressures due to the engine and turbo both relying on each other's performance. So this being the case, we begin setting up the calculations with an ambient air intake temperature but will then relate this to our turbo later.

Since we know the ambient air temperatures and pressure we can calculate the pressure after compression in the cylinder:

\[
P_2 = P_1 \times \frac{V_1}{V_2} \times \frac{T_2}{T_1}
\]
As this is only a temporary number until the turbo and intercooler are factored in we do not need to read too much into it. Knowing $P_2$ and being able to lookup gamma from steam tables means we can now calculate the temperature at $P_2$:

$$
2 = 1 \times \left( \frac{2}{1} \right) \quad (\cdot)
$$

Again this will change near the end of the cycle. We now add the Heat Energy that combusting the Petrol gives. This is done by taking the mass flow rate of air then dividing it by the air/fuel ratio. this gives us the mass of fuel that is going to be used. this multiplied by the Fuel Energy gives how much energy our air/fuel mixture contains. This is then multiplied with the 'specific heat capacity at fixed volume for air' $C_v$ and the mass flow rate ends up giving us post combustion temperature. These are shown below:

$$
\frac{\dot{m}}{\dot{m}} = \left( \frac{\dot{m}}{\dot{m}} \right)
$$

$$
3 = \left( \frac{\dot{m}}{\dot{m}} \right) + 2
$$

$P_4$ can be crudely found by dividing $P_3$ by the $Cr$ again. I did say this was a simplified model! In reality there are several factors that would affect $P_4$ such as cam durations etc. $T_4$ is found in a similar way to $T_2$ but with the Pressures from stages 3 and 4.

$$
4 = 3 \times \left( \frac{3}{4} \right) \quad (\cdot)
$$

So the Heat Energy involved in this engine:

$$
= \dot{m} \times ( 3 - 2 )
$$

$$
= \dot{m} \times ( 4 - 1 )
$$

$$
=\quad =\quad =\quad =\quad = 1 - (\cdot)
$$

Turbocharger

Now we move onto the turbo itself. We have to define what turbo we are going to use so that the various efficiencies can be taken into account. The turbo selected for this application is a Garrett GT32 (For full specification see Appendix 1). We start with the Turbine side and take $T_4$ from the engine as the input temperature for the turbo. The turbine output is designated as $T_5$.

Turbine

Firstly the Mass Flow rate of air needs to be changed from kg/s to lb/min so we can use Garrett's supplied graph. Having done this we need to adjust the air flow so that it is 'corrected' or in other
words set to a standard. As we know the boost in this car to be 10.5 psi we calculate the Pressure Ratio. This now means we can find a point on the turbo graph that corresponds to the figures and thankfully we're as close to optimum efficiency that we can use that number. P5 is found by multiplying P4 by the efficiency . T5 is then found like before for T2 and T4. These are all shown below:

\[
\text{ṁ( /min)} = \text{ṁ( / )} \times 132.27513 = 21.067 / \text{min} \\
\text{ṁ} = \text{ṁ} \times \frac{10.5 + 14.7}{14.7} = 1.71 \\
= 0.68 \\
5 = 4 \times \frac{5}{4} = 118116 \\
5 = 4 \times 14.7 = 468.29 ° \\
\]

We can also calculate the heat lost from the turbine.

\[
= \text{ṁ} \times 4 - 5 = 31247 \\
= 112020 - 31247 = 80772 \\
= 80772 \\
\]

**Compressor**

Next is the compressor. We have slightly different equations for the compressor (as found on p69 of 'Forced Induction Performance Tuning' by A. Graham Bell. See ). We know T6 and P6 as they are ambient air conditions. The compressor efficiency needs to found first, followed by the temperature increase this compression brings. This is as follows:

\[
6 = 290° \quad 6 = 101325 \\
\]

The Pressure Ratio is the same as before so according to the compressor map:

\[
= 0.75 \\
\]

Now according to the book reference mentioned above(Figure 20), the equation for the temperature increase is:

\[
= \text{E} + 273 \times 100 \\
\]

where E is efficiency or \( \eta \) and F is our Compression Factor. Obviously At in this equation in Celsius and is being converted to Kelvin but as the spreadsheet already has this in Kelvin we can bypass this. So this means that:
\[
\frac{0.172 \times 290 \times 100}{0.75} = 66.5^\circ
\]

Figure 20: Factors for Calculating Compressor Outlet Temperatures

Tr now gets added to At(Ambient Temperature) or as has been noted in the report thus far T6. This gives us T7 (Dt7 in spreadsheet), the pre-intercooler temperature. P7 can be calculated from this.

\[
7 = 6 \times \frac{173700}{1.71}
\]

We can also calculate the density of this now hot air boosted to 10.5 psi by means of the formula:

\[
\frac{6 \times 1.39}{7} = 1.39:1
\]

This means that the Air going into the engine is 39% denser than atmospheric which in theory means there should be close to a 39% power increase in the engine. However we need to add some generic intercooler numbers to make the engine output calculations more realistic.
**Intercooler**

The intercooler is basically an air-to-air heat exchanger designed to cool the newly pressurised intake air. $T_7$ is the input temperature and $P_7$ the input pressure.

We take an intercooler efficiency of 0.7 as this seems to be a fairly standard number. We work out the output temperature based on this:

$$8 = 7 \times 0.7 = 356.5 \times 0.7 = 331.46 \, ^\circ K$$

The intercooler will drop the temperature of the air flowing through it but it will also cause a pressure drop due to resistance the air encounters flowing through the intercooler.

According to Intercooler manufacturer, 'Bell Intercoolers';

"*For good solid performance, the pressure loss across the intercooler ought to be kept to less than 1.0 to 1.5 psi. If any pressure in excess of 4 psi is measured, then the intercooler is not suited for the job and certainly harming the performance.*"

*Bell Intercoolers Tech FAQ, bellintercoolers.com*

To check this we need to find $P_8$:

$$8 = \frac{8 \times 7}{7} = 161494 = 8 - 7 = 12206$$

The pressure Drop across the intercooler is theoretically 12206 Pa which to compare this to Bell Intercoolers wisdom is 1.83psi. So the intercooler is slightly too big for the job but considering this numbers came from an efficiency this is not a worry.

$T_8$ and $P_8$ now become $T_1$ and $P_1$ for the Engine and the process via the spreadsheet starts again. The engine with these altered numbers gives a theoretical efficiency of 0.457 which sounds pretty ballpark for a petrol internal combustion engine such as this.

_"the most efficient small four-stroke motors are around 43% thermal efficiency (SAE 900648)"_

**Water/Coolant**

The water/coolant running through the turbo as it operates needs to be analysed especially as far as its inertial properties and flow rates are concerned especially as this will be the clincher in whether or not this concept can be further developed. We start by calculating some basic aspects of the geometry then the heat transferring properties of the is system.

So knowing the inner shaft diameter and the shaft length we can determine the flow area and flow volume before the screw is factored in. We can use ProEngineer to determine aspects such as the shaft flow volume minus the screw volume. Then if this flow is divided by the number of turns in the
screw then the fluid displaced per revolution can be determined. This can then be calculated against shaft speed to give a volumetric and mass flow rate.

**Figure 21: Shaft Geometric Calculations**

As shown in Figure 21, if the shaft were to spin at 60,000rpm (1000rps) the ideal displacement of fluid would be 0.0137m³/s (82.4 l/min) and the resultant Mass Flow Rate would be 13.7kg/s.

**Figure 22: Concept Flow Calculations**

To explain the calculations in Figure 22, we begin with inputting the screw angle which is found by using:

\[
\tan \theta = \frac{\phi}{h} = \frac{0.05}{0.015} = 11.12
\]

We use the shaft's rotational velocity to find the Shaft's 'Shaft Linear Velocity' of 214.86 m/s. Then apply the screw angle to it to find the Horizontal component of the velocity:

\[
= \ast = 214.86 \ast \tan 11.12 = 42.24 \text{ m/s}
\]

We can also find out how long it takes water/coolant to get from one end of the shaft to the other by taking the shaft length and dividing by horizontal speed.

Now we get into the flow itself. Again this is a simplified model but we should hopefully get a good idea of how well the concept will work.

First we need to find the fluid velocity in both the idealised shaft and the water jackets. This is done using:

\[
= \ast 21.22
\]

where \( Q \) is the flow rate in litres per minute and \( D \) is the inner diameter of the pipe.
We then use this to find the Reynolds number of the fluid in the shaft and in the water jackets as they are different geometries. The Reynolds number is found by:

\[ Re = \frac{\rho V D}{\mu} \]

We then find out Kinematic Viscosity (V), Friction Coefficient (\(\lambda\)) and Relative Roughness k/d (f) as these will help with our pressure drop equations. Kinematic Viscosity is calculated using Dynamic Viscosity (\(\mu\)) divided by Density (\(\rho\)).

The friction coefficient and Relative roughness in this case were calculated using Colebrook's Equation:

\[ \frac{1}{\sqrt{\lambda}} = -2 \log \left( \frac{2.51}{Re \sqrt{\lambda}} + \frac{k}{d} \right) / 3.72 \]

Another method of obtaining the Friction Coefficient is to use a Moody Diagram as shown in Figure 23.

To save time an online calculator was used to get the \(\lambda\) & f figures for this scenario - they are as can be seen in Figure 22. Having calculated these, we can, using extra geometry information about the water jackets determine the pressure drop seen at both water jackets and the shaft.

\[ \Delta = \star \star \star \]

Taking the Pressure Drop values for the two water jackets and the shaft together gives us the total pressure drop for the system. When the pressure drop is greater than the input atmospheric pressure Cavitation will occur. According to these numbers, Cavitation occurs at 81,500rpm (± 500rpm) as Pressure Drop across system is the same as atmospheric.
Inertias

Another big issue with this concept is the fact that, certainly in automotive situations, there needs to be as little inertia in the turbo system as possible so that the turbo can respond quickly to demand and get up to efficient boost speeds quickly.

This is where the ProEngineer model comes in handy again. The Shaft and even the water within the shaft were modelled so that with the click of a button, the software calculates the $I_{xx}$ Inertia values.

![Table showing inertia values](image)

Figure 25 shows the numbers lifted from ProEngineer but the parts with this data can be seen in Appendix 2. The Inertia for the 'Comparative shaft' came from a rework of the concepts shaft but instead of being $Ø60$mm and hollow it became a solid $Ø15$mm shaft.

As can be seen the concept's Inertia is 341% of the Comparative's Inertia which is sizeable considering the real world turbo shafts are likely to be thinner and lighter still. This will seriously hamper any kind of response in an automotive situation.
Conclusion

In conclusion it seems that even though this concept may have seemed utterly ridiculous to begin with the theory does actually hold its own quite well, it just falls at the fact that it cannot spool up at any great speed and cannot ultimately revolve at as high speeds as normal turbos. On the plus side the concept would seem to work in a steady state environment and its cooling abilities would prevent the compressor side from heating up due to heat-soak or conduction. This also means it would recover heat otherwise lost which could be useful.

Problems Encountered

- Project/Turbo Complexity - Turbos are a very complex piece of kit that are also very finely engineered with very close tolerances as they would have to revving as high as they do.
- Lack of Computational Knowledge - I would have loved to have applied CFD to this to try and get some simulated heat transfer or Inertial studies but my knowledge is still too limited for this.
- Time Constraints - For the complexity of the project, 12 weeks was not enough time with everything else going on. Having my data stolen at week 6 didn't help at all either!

Future Work

There is a surprising amount of future work that could be done on this project as the concept has been shown to work:

- Full CFD Investigation
- Investigate Concept in other Contexts for example Marine Diesel Engines
- Further Analysis of Inertial and Mass Properties
- Produce models to test and verify flow rates/speeds etc
Literature Review

Four Stroke Engine Theory
Four stroke petrol engines have been about for years, and in case there was any doubt to the basics of their operation, A. Graham Bell (2006) uses his in-depth knowledge to explain at engineer level and beginners level the various systems. The book 'Four Stroke Performance Tuning' is very good at what it is describing but relatively speaking it is not that relevant to this project.

Forced Induction Theory
However 'Forced Induction Performance Tuning' (A. Graham Bell - 2002) is a lot more appropriate. It makes for a good read and as a good chunk of it focuses on learning from the past endeavours of racing teams and manufacturers it provides a good insight into how this proposed concept may work. Toshimitsu Tetsui (2002) investigates the uses of Titanium Alloys in turbochargers to withstand higher temperatures, improve response and mostly for the sake of endurance. He talks in depth about the material characteristics but all-in-all it is not a massively useful paper for this project as the design in this project is purely to show and put numbers to it. 150hp 'Oil-Free' turbochargers being successfully demonstrated (Hooshang Heshmat, PhD., Fellow ASME & STLE James F. Walton II - 2000) could potentially be a great addition to this project as the temperatures and turbo revolutions are relatively low compared to standard turbochargers.

Heat Exchanging Theory
Aydin Durmus (2002) studies a heat exchanger with a snail entrance. The actual heat exchanging aspect of it is a bit too in-depth for this but it did provide a useful insight into the heat losses the turbine may see and its geometry. A slightly irrelevant paper but with a lot of potential for future studying of this project has L.Z. Zhang (1999) discussing exhaust driven heat exchangers with the idea of recapturing heat energy otherwise lost - not too dissimilar a brief to my own but its detail is in the materials and testing of the concept.

References
A. Graham Bell, "Forced Induction Performance Tuning" - 2002
A. Graham Bell, "Four Stroke Performance Tuning - 3rd Edition" - 2006
Yuval Doron, Meen-646 turbomachinery Flow Physics, "Design Of An Integrated Turbocharger", Dr. T. Schobeiri - 2009
Toshimitsu Tetsui, "Development of a TiAl turbocharger for passenger vehicles" - 2002
Chris Rorres, "The Turn Of The Screw: Optimal Design Of An Archimedes Screw"- 2000
Aydin Durmus, "Heat Transfer and Exergy Loss in a Concentric Heat Exchanger with Snail Entrance" - 2002
L.Z. Zhang, "Design and testing of an automobile waste heat adsorption cooling system" - 1999

Other Resources
- Lecture material from UWS Hamilton lecturers Mr D Kennedy and Dr S McIlwain.
- Garrett Turbochargers
- Bell Intercoolers
- 4wings.com - Pressure Drop Information
- engineeringtoolbox.com - Engineering Equations
Appendix 2

Figure 26: Modelled Ideal Water sized the same as the shaft with the screw cut-out of it.

Figure 27: Modelled 'Comparative Shaft'