Design and Analysis of A Turbocharged Single Cylinder Diesel Engine Intake System For Increased Power Output and Transient Response

by

Orlando Ward-Santos

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Mechanical Engineering at the Massachusetts Institute of Technology

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Signature redacted

Signature redacted

Certified by: Aplos G. Winter, V
Assistant Professor of Mechanical Engineering
Thesis Supervisor

Signature redacted

Certified by: Rohit Karnik
Associate Professor of Mechanical Engineering
Undergraduate Officer
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ABSTRACT

Small displacement, single-cylinder diesel engines have many applications in developing countries such as small-powered agricultural equipment, water pumps, and other power sources. Research has shown that the power of a turbocharged single-cylinder engine can match that of a larger displacement multi-cylinder, naturally aspirated engine, at a fraction of the cost. The valve timing mismatch that occurs when turbocharging a single cylinder engine is solved by adding a large volume air intake as a buffer for the pressurized air. This thesis explores the design, methodology, and testing of modifying the additional air intake to passively varying its volume during operation. Mechanical design of the variable volume air capacitor is established. Next, the experimental setup is discussed. Finally, both steady state and transient experimental results are discussed.

Thesis Supervisor: Amos G. Winter, V
Title: Professor of Mechanical Engineering
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1 Introduction

This thesis presents the mechanical design of an air capacitor used in turbocharging single-cylinder, four-stroke engines, optimized for improved performance. The air capacitor is a buffer in the form of a large volume intake manifold which sits in between the turbo’s exhaust and engine intake, as shown in figure 1-1, first proposed as a means for compensating for the mismatch between engine intake and exhaust timings by Professor Amos G. Winter, V. [6]. The air capacitor is what stores the pressurized air and ultimately delivers it to the engine between engine cycles.
Various design parameters such as sizing, geometry, and material selection greatly affect the system's steady state and transient response. This thesis proposes the mechanical design and testing of a variable volume air capacitor to specifically address these steady state and transient issues.

As the pressure within the intake manifold varies, the variable volume air capacitor adjusts the volume of the system to compensate for over pressurization, or lack of pressure, allowing for improvements in pressurization time and an increase in system power output. The proposed design includes a piston and chamber subsystem that bolts onto a retrofitted air capacitor. The subsystem is designed for low leakage rates; smooth, low-friction, linear motion; and passive actuation.

1.1 Motivation

This technology targets applications such as low-powered agricultural equipment, tractors, water pumps, and generators in the developing world. Development of a turbocharged, single-cylinder diesel engine system to replace current naturally aspirated, multi-cylinder engines has been proven to match expected power outputs at lower cost and greater system efficiency [1]. Previous research in Indian markets suggest that available farm power and mechanization has the greatest influence in crop yield amongst small-scale farmers [2]. Introduction of low-cost solution to Indian and similar markets could promote small-scale farmer productivity.
2 Background

The goal of this section is to give the reader background understanding of relevant technology so that the reader may have a better grasp and understand the significance of the newly proposed system.

2.1 Diesel Engine Cycle

The Diesel cycle consists of four main strokes. First, air is pulled into the engine through the intake stroke. Next, in the compression stroke, once the air has collected inside the piston chamber, it is compressed to the point where by adding fuel, the mixture will undergo combustion. As diesel fuel is injected into the cylinder during the power stroke, the mixture combusts, pushing against the piston body. Finally, the exhaust stroke occurs as the piston expands, the exhaust valve opens, and the combusted mixture is expelled from the engine [3].
2.2 Turbocharging

Engine power outputs are directly related and limited by the amount of air the engine intakes due to the stoichiometric relation between the fuel-air mixture. Naturally aspirated engines are limited to intaking air at ambient pressures. Turbocharges however, use exhaust gas from the engine to power a turbine, mechanically coupled to a compressor, which compresses incoming air. Now, as opposed to air at ambient pressures, the compressor supplies the engine with pressurized air, increasing the air intake density.
Turbocharging a naturally aspirated engine ultimately increases its peak power output. Compared to its multi-cylinder counterpart, a smaller, single-cylinder, turbocharged engine can meet similar power demands at higher fuel efficiencies.

As outlined in John Heywood’s *Internal Combustion Engines*, an internal combustion engine’s energy balance shows that only a fraction (34% - 38%) of the available energy is converted into useful, usable energy [3]. The remaining energy balances follows:

- **Break Power**: 34% - 38%
- **Exhaust Losses**: 22% - 35%
- **Cooling Losses**: 16% - 35%
- **Incomplete combustion Losses**: 1% - 2%.
- **Other Thermal Losses**: 2% - 6%
The remaining energy is lost in the during the process. A significant amount of energy is lost in the form of heat through frictional losses in the system. With every engine stroke, as the piston slides inside the chamber, heat is generated from the metal-to-metal contact. Since the amount of heat generated is directly proportional to the amount of surface area, multi-cylinder engines generate more heat, leading to greater frictional losses. Turbocharging an engine decreases the amount of needed chamber volume by compensating with increased intake air density [3].

One concern with turbochargers is turbo lag. Turbo lag refers to the amount of time it takes for the exhaust gases from the engine to spool up the turbine. Before adequate spool up, the compressor is unable to pressurize the incoming air and instead increases the dynamic pressure drop in the system by increasing minor losses. Adding the capacitor to the system, increases the intake manifold volume, thus negatively affecting the spool up time needed to pressurize the air capacitor. Due to this, previous work with turbocharged single-cylinder engines using an air capacitor as a buffer have targeted steady state operations [9]. The proposed variable volume cylinder seeks to improve the transient response of the system and decrease turbo lag.

2.3 Air Capacitor

The air capacitor acts as a buffer between the pressurized air leaving the turbocharger compressor and the engine intake due to valve timing mismatch in a single-cylinder engine. Previous work has developed governing equations and validated models to determine capacitor sizing for optimal pressurization times and minimal pressure drop.
Simplified isotropic expansion analysis of the working fluid showed that a capacitor volume 5.8x that of the engine volume would be necessary to maintain 80% of the initial pressurization in the intake manifold [1]. A fill model for the air capacitor was also previously developed to look at the relationship between air capacitor pressurization time and tube diameter. Modeling showed that fill time was very sensitive to tube diameter, showing that for tube diameters greater than 3 centimeters, it would take less than one second to fill the capacitor [1].

3 Experimental Overview

This section gives a detailed overview of the mechanical design of the modified air capacitor and its variable volume mechanism. Analysis of materials and design of various parameters of the variable volume capacitor is described below. Design and setup of the experiment is then described, with details regarding retrofitted manifold designs, engine, and dyno instrumentation used, followed by a brief overview of the testing procedure.

3.1 Capacitor Design

Thoughtful design of the air capacitor is needed to meet the design requirements and proper operation. The capacitor needs to withstand internal pressures from the boosted intake system. Its thermal resistance of the system must be high enough to maintain the steady state temperature of the intake air at reasonable temperatures. Similarly, its thermal mass needs to be able to maintain the intake air temperature at reasonable values during transient events. The actuated piston within the capacitor needs to be supported by low friction bushings to overcome any expected radial and thrust loadings. The system require passive actuation by a spring
mechanism to modulate its volume during operation. Lastly, the chamber must be designed to provide adequate sealing at low leakage rates throughout its motion.

![Isometric view of variable volume air capacitor](image)

**Figure 3-1:** Isometric view of variable volume air capacitor

Initial sizing for the air capacitor was based off of previous work with fixed volume air capacitors. Research shows that an air capacitor of roughly 5.8x the volume of the displaced volume of the engine maintains the initial pressurized air in the intake at 80% of its initial value when it flows into the engine [1,10] Given the 0.44 liter engine used for testing, the fixed volume part of the variable volume air capacitor was sized. The variable volume piston allows for roughly a liter of variability, 0.5 liters of expansion and 0.5 liters of compression.
3.1.1 Mechanical Strength

Boosted intake pressures can reach values of up to 7 psi in the manifold system [1]. The air capacitor material selection and thickness must be designed to withstand these forces within reasonable factors of safety to account for fatigue loading and decreases in material strength around heat affected zones from welding. For ease of manufacturing, 1018 carbon steel with various thicknesses (1/8in., 3/16in., 1/4in.) available through McMaster-Carr were considered. A simplified analysis of loading the longest face of the capacitor with the force from the internal pressure acting on that face was used to iterate through various thicknesses.
Ultimately, \( \frac{3}{8} \) inch thick steel tubing could withstand max internal pressures with factor of safety (F.O.S = 1.14), based on McMaster material properties and loading conditions, thus was selected for the capacitor tubing.

3.1.2 Shaft mechanism

The variable volume air capacitor actuation mechanism is in the form of piston constrained to linear motion by two bronze bushings. In addition to constraining the motion of the piston, the bushings support the bending and radial loads on the shaft, as well as provide a smooth motion with as little friction loss as possible. Readily available oil-impregnated bronze bushing were selected to support the expected forces. The longest available bushing lengths were also chosen to allow for the greater support throughout the travel of the shaft and minimize stress on the shaft.
Figure 3-4 Cross sectional view of the variable volume air capacitor piston and shaft mechanism

Any frictional loss in the bushings will occur due to misalignment in the shaft mechanism translating to a frictional force as the shaft rubs against the bushings. To compare between varying bushing materials, the max intake pressure of 7 psi acting on the piston, and an assumed max misalignment angle of 3 degrees was considered. The max normal force acting on the bushings were iterated through varying material-on-material coefficient of frictions. The selected oil-impregnated bronze bushing on aluminum shaft showed decrease in power loss by nearly a factor of 4 when compared to clean aluminum on aluminum.
To avoid stress on the bushings due to misalignment, the bushing holders are designed to ‘float’ during assembly until the piston shaft is used to locate the bushing relative to one another, then the holders are secured. To achieve this, all bolted connections securing the bushing holders to the main piston chamber are drilled to loose fit clearance hole sizes. The loose fit diminishes the risk of over constraining the system and allows for enough planar ‘play’ in the system to allow for accurate constraints.

### 3.1.3 Spring Selection

The linear motion actuation of the variable volume capacitor is passively controlled with a linear force compression spring. The piston shaft sits inside the spring, allowing for any linear translation in the piston shaft to also be translated to the spring. The stiffness of all metal components in the shaft system are orders of magnitude stiffer than the compression spring, thus the spring stiffness may be assumed to be the effective stiffness of the system. As the pressure
inside the capacitor increases, the force acting on the piston increases, compressing the spring. Selection of spring stiffness directly translates to the amount of volume change the capacitor achieves for a given intake air pressure range. A softer spring translates a given pressure range to a more dynamic volume range when compared to a stiffer spring which would cause little volume change, ultimately compared to a fixed volume capacitor with no volume change.

3.2 Experimental Setup

The following section provides a brief description of the various other components within the context of the experiment with justification for their selection and design.

3.2.1 Manifolds

Retrofitted intake and exhaust manifolds needs to be designed and made to adapt the turbocharger to the engine. Careful consideration of thermal and mechanical loading, sealing, and ease of manufacturing were taken into account during design of the systems.

The biggest concern from previous experiments was the lack of sealing at all of the manifold connections [1]. Insufficient material thickness to allow for bolt pressure cone overlapping, improper use of gasket material selection, and inadequate hardware selection and torquing settings is thought to have attributed to much of the pressure drop throughout the system. Any increase in pressure drop in either the intake or the exhaust leads to loss of power and potentially misinterpreted experimental data. The current design of the manifolds addresses these issues.
A conservative estimate of a 30 degree bolt pressure cone was used to size the thickness of the manifold plates. High temperature and high pressure graphite gasket material was used to further allow for a uniform seal. The graphite gasket material was rated up to 2,000 psi and 850 degrees Fahrenheit, well above even the engine's expected exhaust pressures and temperatures.

Figure 3-6: Front view of the turbine inlet manifold showing the overlap in bolt pressure cones needed to properly seal in air passage.

Ease of manufacturing was also important in the design of the new manifold systems. A combination of welded flat plate stock and tube was used to allow for quick turnaround times and ease of manufacturing.
3.2.2 Engine

The engine used for this experiment was a Kohler KD440, a 0.44 liter single cylinder, four stroke diesel engine. The engine had a maximum power output of 9.1 horsepower and a gross torque of 16.2 ft-lbs. In addition to the engine's wide use throughout industry for various applications and its proven durability [7]. In addition, it is equipped with an easily adjustable
mechanical governor to allow for flexibility in speed control; its mechanical design allows for flexible, easy access to its intake and exhaust manifolds; and new air filtration system, integrated fuel-injection system and overhead cam design, and cast-iron construction for durable design.

Figure 3-8: Kohler KD440, a 0.44 liter single cylinder diesel engine used for testing [7].

3.2.3 Turbocharger

The turbocharger used for this experiment is a copy of the IHI RHB31 turbocharger, made by Ecotrons. The turbocharger is currently the smallest, industry-made turbocharger, suited for engines from 125cc to 600cc. The turbocharger also is made with integrated oil and water cooling paths to lubricate the internal bearings to prevent overheating and increase turbo efficiency.
3.2.4 Dynamometer

The dynamometer that was used for this experiment was a twenty kilowatt eddy current system produced by Taylor Dynamometer [8]. This system allowed for accurate measurement of load, speed, and manifold pressures. The dynamometer integrates well with the engine and provides a flexible, easy platform and software for varied testing on the engine. Load and speed are easily controlled.
3.2.5 Sensors

Accurate sensing is crucial to appropriate data collection. Careful consideration of pressure and temperature levels as well as data collection speed and resolution were taken into account when selecting pressure transducers and thermocouples. Similarly, the linear potentiometer used with the variable volume capacitor was selected based on its linear range and resolution.
3.3 Method

The dynamometer allows for easy speed and load control on the engine. With the test set-up, both steady state and transient response data were conducted. For steady state operation, at a fixed load, the engine was throttled to a range of speeds then allowed time to reach a steady operating point. The steady state operating points are as follows:

3.3.1 Steady State Tests

Load: No Load

Speed Cycle (In RPM): 2000, 2500, 3000, 35000

Load: Half Load (Approximately 4.5 ft-lbs of torque)

Speed Cycle (In RPM): 2000, 2500, 3000, 35000

Load: Rated Load (Approximately 9 ft-lbs of torque)

Speed Cycle (In RPM): 2000, 2500, 3000, 35000
3.3.2 Transient Tests

Transient, torque response test were also carried out to look at the variable capacitor’s behavior with impulse torque responses. For transient operation, a fixed speed was selected then, torque was instantly impulsed from one set point to the next. Transient operating points were as follows:

- Speed: 3000 RPM
- Initial Torque: 0 ft-lbs
- Final Torque: 10 ft-lbs

Test were all performed were performed enough times to generate a 95% confidence interval for each testing condition. The system was tested with a fixed capacitor volume, then with the variable volume capacitor passively actuated by a compression spring.

4 Results and Discussion

This section presents and discusses the results from steady state power and transient torque response tests. For steady state operation, at a fixed load, the engine was throttled to a range of speeds then allowed time to reach a steady operating point. For transient operation, a fixed speed was selected then, torque was instantly impulsed from one set point to the next. Pressure directly before the engine’s intake was observed to show both an increase in steady state power output and an increase in transient response, suggesting an overall improvement in the system from adding the variable air capacitor.
4.1 Steady State Response

The first experiment performed was the steady state test. In this test the load on the
dynamometer was set at either no load (torque = 0 ft-lbs), half load (torque = 4.5 ft-lbs), or full
load (torque = 9 ft-lbs). At each load scenario, the engine was throttled to a specific operating
speed, then allowed to settle to a steady state. Pressure at the engine’s intake was monitored at
each experiment test point. An increase in engine intake pressure has a direct correlation with an
increase in engine power output. Test were all performed were performed enough times to
generate a 95% confidence interval for each testing condition. Figure 4-1 suggests that the
variable volume addition to the air capacitor has a positive increase in the pressure at the
engine’s intake.
Figure 4-1: Shows engine intake pressure values from steady state tests throughout engine operating speeds, at variable loads. Overall, adding the variable volume air capacitor positively increases the measured pressure values at the engine intake.

At higher loads, the turbocharging operates at a higher work output, increasing the pressure inside the intake manifold. Similarly, because the variable volume air capacitor will show the greatest difference in performance at increased intake pressure, tests run at full load illustrate the most significant difference in performance between the fixed volume and variable volume air capacitors. Figure 4-1 suggests a consistent increase in engine intake pressure throughout the engine’s range of operating speeds.
4.1.2 Transient Response

The second experiment was the load response test. In this test the load on the dynamometer was instantaneously increased and the time it took for the engine to react and reach a new equilibrium was measured. Two measures of torque response were obtained from this test. The first measure of torque response is the torque response time. The torque response time is defined in this experiment as the amount of time it takes to go from no load to ten pound feet of torque at a constant speed of 3000 RPM. This time is measured as the time it takes to go from no load (measured from when the load signal was sent to the dynamometer) to the final load (measured where the load is 90% of the way to the final load) is measured. The second measure of torque response was torque response rate. This is the rate that the engine can respond to an
impulse in torque. The slope is measured from two to five pound feet of torque. This gives a value with units of pound feet per second. Figure 4-3 illustrates how these tests were run.

![Variable Volume Air Capacitor](image)

Figure 4-3: Displays how the torque response tests were measured. For each torque impulse set, the red dots represent the start and end of the specific run, used to calculate the time to response to the torque impulse. The green highlighted section represents the smooth section a data use to look at torque response rates.

### 4.2.1 Torque Response Time

Figure 4-4 shows the torque response time for the fixed volume and variable volume cases. This is the amount of time it takes to get to ninety percent of the final load when a torque impulse is applied. It was found that the response time for all of the cases was approximately the same at just over three seconds. The experimental data suggests that the variable volume air capacitor takes less time to respond to a torque impulse.
4.2.2 Torque Response Rate

Figure 4-5 shows the torque response rate for both the variable and fixed volume experimental set-ups. This is the rate of torque response in pound feet per second. The variable volume capacitor shows an increase in torque response rate. As the load increases, the increased pressure in the capacitor actuates the spring, causing the piston to expand or contract as necessary to compensate for the varying pressure. This result shows that the capacitor with variable volume allows the initial response to a torque impulse to be improved.
5 Conclusion

Both steady state and transient response tests suggest that adding the variable volume capacitor in place of the fixed volume capacitor could both increase the steady state power output of the engine, and improve torque impulse response.

5.1 Future Work

Both steady state and transient tests suggest that there are valuable performance benefits to adding a variable volume air capacitor in the single cylinder turbocharged engine design. Before the system can be implemented in industry applications: low-powered agricultural equipment, water pumps, and other forms of power sources, further analysis must be conducted on the system. Future work includes both that might increase reliability and performance of the variable volume capacitor and work that would promote its feasibility as a product.
Performance and reliability of the variable volume capacity is largely based on its: mechanical design, thermal design, and consideration for air leakage. More detailed finite element analysis (FEA) and load case scenarios should be performed to further optimize the capacitor system mass. The air capacitor system is an auxiliary system that would be connected to its paired engine and turbocharger. Lower weight suggests more favorable loading cases such as vibrational loads. Previous work has also shown that engine output power is very sensitive to intake air temperature [1,9]. The current design of the variable volume capacitor is on thin carbon steel plates and tubing. A closer look at the thermal design of the air capacitor could improve the steady state and transient thermal response of the system, leading to engine power benefits. Selected materials and design geometries can be iterated to improve the thermal resistance of the system, leading to an decrease in steady state temperature. Air leakage is another design consideration that should be looked at more closely. The variable volume air capacitor introduces additional moving parts and potential areas for air leakage. The current design tries to address this issue with overlapping bolt pressure cones and soft neoprene rubber gaskets; however, assessment of the design's performance and attempts at better implemented solutions should be considered.
6 References


