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VALIDATING A METHOD FOR TURBOCHARGING SINGLE CYLINDER FOUR STROKE ENGINES

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ABSTRACT

This paper presents a method for turbocharging single cylinder four stroke internal combustion engines, an experimental setup used to test this method, and the results from this experiment. A turbocharged engine has better fuel economy, cost efficiency, and power density than an equivalently sized, naturally aspirated engine. Most multi-cylinder diesel engines are turbocharged for this reason. However, due to the timing mismatch between the exhaust stroke (when the turbocharger is powered) and the intake stroke (when the engine intakes air), turbocharging is not used in commercial single cylinder engines. Single cylinder engines are ubiquitous in developing world off-grid power applications such as tractors, generators, and water pumps due to their low cost. Turbocharging these engines could give users a lower cost and more fuel efficient engine. The proposed solution is to add an air capacitor, in the form of a large volume intake manifold, between the turbocharger compressor and the engine intake to smooth out the flow.

This research builds on a previous theoretical study where the turbocharger, capacitor, and engine system were modeled analytically. In order to validate the theoretical model, an experimental setup was created around a single cylinder four stroke diesel engine. A typical developing world engine was chosen and was fitted with a turbocharger. A series of sensors were added to this engine to measure pressure, temperature, and power output. Our tests showed that a turbocharger and air capacitor could be successfully fitted to a single cylinder engine to increase intake air density by forty-three percent and peak power output by twenty-nine percent.

NOMENCLATURE

A Cross sectional area of connecting tube
D Diameter of connecting tube
F Friction factor
K Minor losses
L Length of connecting tube
m_c Mass of gas inside the capacitor
$\dot{m}_c$ Mass flow rate of gas into the capacitor
$\dot{m}_t$ Mass flow rate of gas at turbocharger
P_C Pressure inside the capacitor
P_e Pressure in the engine at the end of the intake stroke
P_t Pressure at the turbocharger
P_0 Initial pressure inside the capacitor
$\dot{P}_C$ Rate of pressure change inside the capacitor
R Specific gas constant
T_C Temperature inside the capacitor
T_t Temperature at the turbocharger
V_C Volume of the capacitor
V_e Volume of the engine
v_s Velocity of air in connecting tube
γ Heat capacity ratio (1.4 for air)
ρ_C Density of air inside the capacitor
ρ_t Density of air at the turbocharger

INTRODUCTION

A turbocharger pressurizes the intake stream of an engine, causing it to combust more fuel and produce more power than an equivalently sized naturally aspirated engine. A turbocharger consists of a turbine and a compressor connected by a shaft. The turbine is powered by the high temperature and pressure exhaust gas leaving the engine during the exhaust stroke [1,2]. The compressor, which is powered by the turbine, compresses the air going into the intake of the engine.

There are three main advantages of a turbocharged engine over a naturally aspirated engine. First a turbocharged engine costs less than a naturally aspirated engine with the same power rating. According to an original equipment manufacturer in India, a turbocharger costs eighty percent less than adding a second cylinder [3]. The second is that a turbocharged engine is more fuel efficient than a naturally aspirated engine with the same power rating. This is because turbocharged engines are smaller and, as a result, have less frictional losses [4]. The third advantage of a turocharged engine is that it has a higher power density compared to a naturally aspirated engine [5].

The application being targeted for our technology is low-cost agricultural equipment. Turbocharged single cylinder engines could replace naturally aspirated engines in water pumps, generators, and tractors making more power available for farmers at lower costs. This technology could open up a new market of small scale farmers who, in the past, could not afford mechanization. Research in the Indian market has shown a direct correlation between food yield and a number of factors including rain fall, fertilizer availability, available farm power, and median income [6]. This study showed that farm yield is most closely correlated to available farm power (Fig. 1). In addition to low cost agriculture, our technology could be used in single cylinder applications in wealthy countries, such as small UAVs, motorcycles, and household generators.

Most modern multi-cylinder diesel engines are turbocharged due to the multiple benefits of turbocharging listed earlier. A multi-cylinder engine can be designed in such a way that when one cylinder is going through the exhaust stroke, powering the turbocharger, another cylinder is intaking [1,2]. In a single cylinder engine there is a phase difference between the intake and exhaust stroke. This means when the engine is exhausting, which is when the turbocharger is powered, the engine is not intaking and the air has nowhere to go. In addition to this, turbochargers under pulsating conditions have been shown to act irregularly, and have pressure profiles that vary significantly [7]. Due to the varying nature of turbochargers and the phase mismatch between the intake and exhaust strokes, commercial single cylinder engines are not currently turbocharged despite the numerous potential advantages.

This paper presents an experiment to validate a means of turbocharging single cylinder four stroke engines. The proposed method is to add a buffer in the form of a large volume intake manifold, which we call an air capacitor, to store compressed air between the intake strokes (Fig. 2). This method for turbocharging single cylinder engines was first presented at the 2014 IDETC conference [8]. This work will review the theory that was discussed previously, describe an experiment designed to validate the method, and the initial results from this experiment. The goal of this research was to validate our methodology for turbocharging single cylinder, four stroke, internal combustion engines.

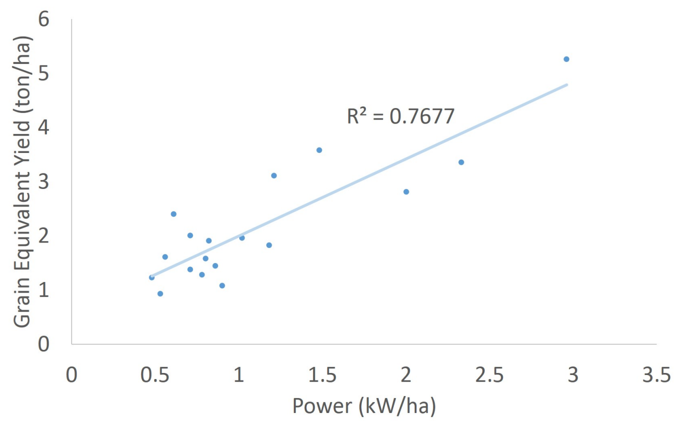

FIGURE 1. CORRELATION BETWEEN FARM POWER AND YIELD

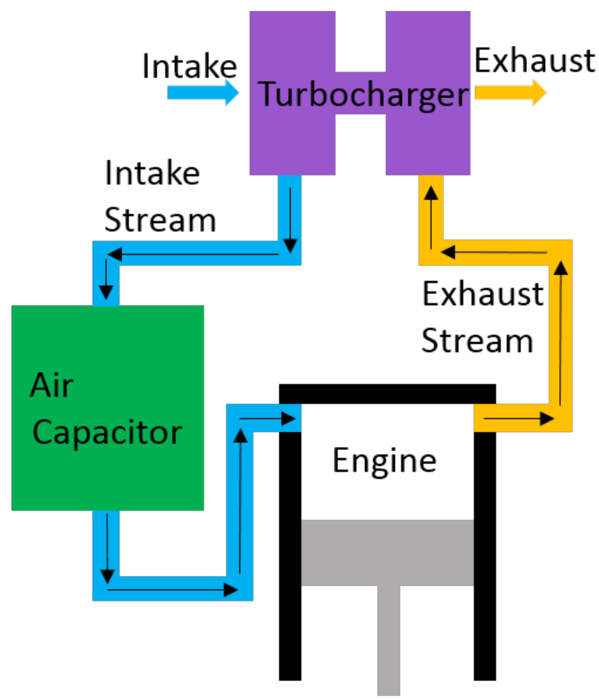

FIGURE 2. BLOCK DIAGRAM OF ENGINE FLOW WITH AIR CAPACITOR SYSTEM

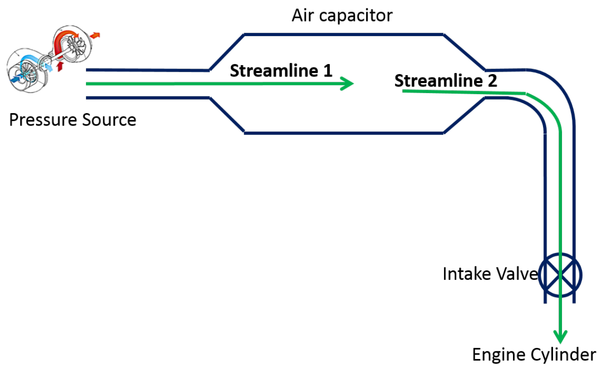

FIGURE 3. DIAGRAM OF THE FULL INTAKE MODEL

THEORY

Before designing and building an experimental setup, a theoretical model of how air flows through the intake manifold was developed. This model started with a simple constant pressure source fill model and was built up into a model that describes flow through the manifold [9]. Details of how this model was developed are described in a 2014 IDETC conference paper [8]. The final model (Fig. 3) characterized the flow through the entire intake manifold. The goal of the model is to find the density gain of the intake air due to turbocharging, which to first order is proportional to the power gain [4].

The model treats the turbocharger as a variable pressure source, whereby it applies the full turbo pressure to the air capacitor during the exhaust stroke, and no additional air flow during the intake, compression, and power strokes. This assumption on how the turbocharger behaves is based on studies of a turbocharger under pulsating inlet conditions [7]. The engine was modeled as a variable volume vessel that took air from the capacitor during the intake stroke. Two streamlines were defined, one between the turbocharger and the capacitor and the other between the capacitor and the engine. Conservation of mass and the ideal gas law were also used in creating the final model. The derivation of the equations that describe the flow along each streamline is shown below in equations 1 through 12 [8]. It was found that the pressure in the capacitor is described by a nonlinear, first-order differential equation that must be solved computationally [8].

$$\frac{P_t - P_C}{\rho_t} = \frac{v_s^2}{2} + \frac{FL}{D}\frac{v_s^2}{2} + k\frac{v_s^2}{2} \tag{1}$$

$$\dot{m}_s = \rho_t v_s A \tag{2}$$

$$\dot{m}_C = \frac{\dot{P}_C V_C}{RT_C} \tag{3}$$

$$\dot{m}_C = \dot{m}_S \tag{4}$$

$$\rho_t v_s A = \frac{\dot{P}_C V_C}{RT_C} \tag{5}$$

$$v_s = \frac{\dot{P}_C V_C}{\rho_t A R T_C} \tag{6}$$

$$\frac{P_t - P_C}{\rho_t} = (\frac{1}{2} + \frac{FL}{2D} + \frac{k}{2})v_s^2 \tag{7}$$

$$\frac{P_t - P_C}{\rho_t} = (\frac{1}{2} + \frac{FL}{2D} + \frac{k}{2})(\frac{\dot{P}_C^2 V_C^2}{\rho_t^2 A^2 R^2 T_C^2}) \tag{8}$$

$$P_t - P_C = (\frac{1}{2} + \frac{FL}{2D} + \frac{k}{2})(\frac{\dot{P}_C^2 V_C^2}{\rho_t A^2 R^2 T_C^2}) \tag{9}$$

$$C = \frac{\rho_t A^2 R^2 T_C^2}{(\frac{1}{2} + \frac{FL}{2D} + \frac{k}{2})V_C^2} \tag{10}$$

$$P_t - P_C = \frac{1}{C}\dot{P}_C^2 \tag{11}$$

$$\dot{P}_C^2 + CP_C - CP_t = 0 \tag{12}$$

We considered two cases with this model. The first is where there is perfect heat transfer out of the air capacitor. This is the best case scenario where the density gain will match the pressure gain. The second is where there is no heat transfer in the intake manifold. This is the worst case scenario, where density gain will be less than pressure gain. In reality, the system will operate somewhere between these two extremes. The results of this model for an engine running at 3600 RPM with a 13 psi gage turbo pressure, and an 18:1 compression ratio is shown in Fig. 4 (These operating conditions are similar to those of engines used in the developing world and in the experiment). This plot shows density gain as a function of non-dimensional capacitor volume which is the ratio of the capacitors volume to the engines volume. It was found that without heat exchange there is a density gain of approximately thirty-five percent, and with perfect heat exchange there is a density gain of approximately fifty-five percent. It was also shown that as capacitor volume increases there is diminishing marginal increases in intake density.

EXPERIMENT DESIGN

The goal of this experiment was to demonstrate that a single cylinder engine could be turbocharged and to test how the engine performs with different volume air capacitors. In order to keep the experiment setup simple, four key performance metrics were chosen: air capacitor volume, intake air density, engine speed, and power output. From these metrics viability of the air capacitor could be verified. Emissions quality, fuel efficiency and exhaust pressure are other interesting metrics, but they would be costly to study, and are not relevant to the testing of the turbocharging scheme. These metrics will be measured in the future.

The experiment was designed to be as simple as possible. The result was a basic dynamometer made from a low-cost diesel generator (Fig. 5). The diesel engine selected for the dynamome-

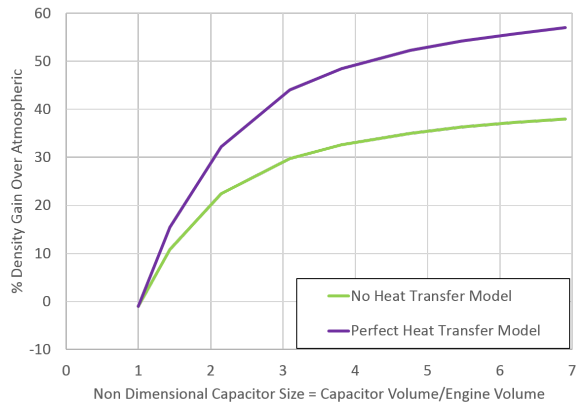

FIGURE 4. THE RESULTS OF THE THEORETICAL MODEL WITH AND WITHOUT COOLING ARE SHOWN AS A FUNCTION OF CAPACITOR SIZE. DENSITY IS NON-DIMENSIONALIZED BY ATMOSPHERIC AIR DENSITY.

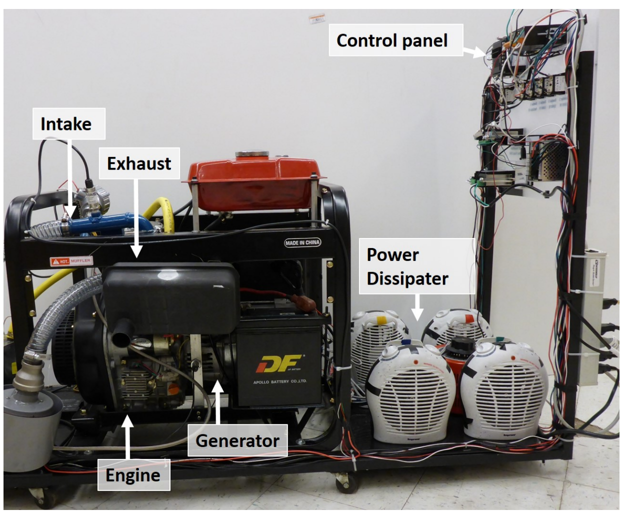

FIGURE 5. PHOTOGRAPH OF THE DYNAMOMETER USED

FIGURE 6. THE AIR CAPACITORS BUILT FOR THIS SETUP THAT ALLOWED FOR DIFFERENT INTAKE MANIFOLD VOLUMES

ter was a Koop model KD186FA. This engine was selected because it has a large volume (0.418 L). It is a four stroke single cylinder diesel engine, it is similar to engines used in the developing world (low cost, made in China), and it is available from Home Depot already integrated into a generator. Because the engine came as part of a generator, there was no need to fit a power dissipation unit to the engine. An electrical load can be applied to the generator to apply a load to the engine.

The Garrett GT0632SZ turbocharger was selected to be fitted to this engine. It was selected because it was one of the smallest available turbochargers, designed for engines between 0.1 and 0.5 liters, and a version of this turbocharger is already used by Mahindra, an Indian power products manufacturer, on some of its two cylinder products. In order to fit a turbocharger to this engine the intake and exhaust system were stripped. Then a custom exhaust manifold was designed to couple the turbocharger to the engine. It was designed to be as small as possible in order to prevent the air from cooling between the engine and the turbocharger. The manifold was cut out of steel plates with a water jet then welded together. An adapter was built to couple the turbocharger outlet to the muffler.

A separate oil system was fitted to the turbocharger in order to lubricate the bearings. An air filter was chosen and connected to the turbocharger's compressor intake using 1.25" ID rigid tubing. The engine intake was fitted with a custom made adapter that converted the stock engine intake fitting into a female one-inch NPT pipe fitting. The adapter was also fitted with a temperature sensor and a pressure sensor placed as close to the engine as possible. This fitting allowed for different sized air capacitors to be attached to the engine (Figs. 6, 7, and 8). Another pressure sensor was fitted close to the turbocharger's compressor outlet. The results of these modifications was an engine with a new intake and exhaust system that included a turbocharger (Fig. 9).

Space heaters were attached to the generator in order to provide a controlled load on the engine. Six space heaters were used and each could provide a load of up to 1600 watts. Five of the space heaters were wired to the generator through switches that the operator could control. The fourth space heater was wired to the engine through a variable AC power transformer that the operator could control. This allowed for the space heater to provide a load anywhere between zero and 1600 watts. As a result, the power dissipation system could provide a load of anywhere between 0 and 9600 watts on the engine. The load on the engine was measured by a power-meter that displayed the output voltage and current coming out of the generator. The whole dynamometer system is monitored and controlled through a central control panel (Fig. 10). The panel allows the operator to vary the load on the engine and easily view and log the data coming from the

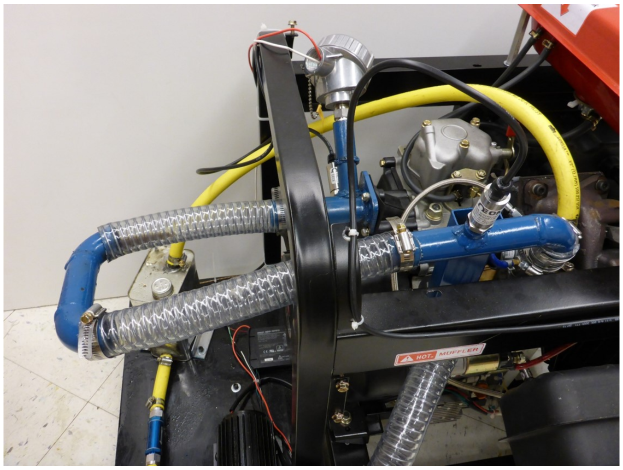

FIGURE 7. INTAKE MANIFOLD WITH NO AIR CAPACITOR, 0.9 L TOTAL MANIFOLD VOLUME

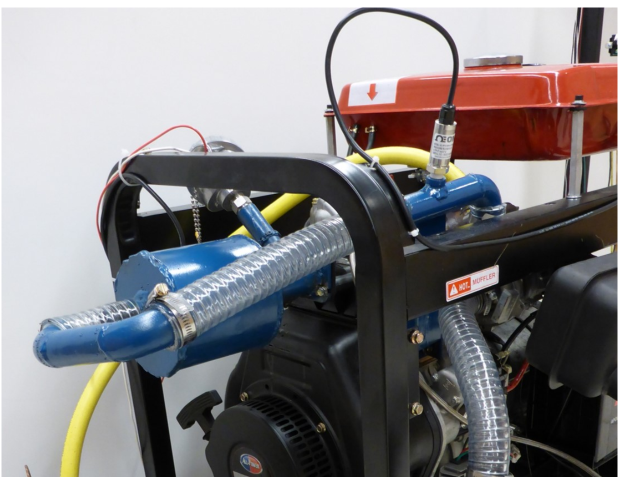

FIGURE 8. INTAKE MANIFOLD WITH A MEDIUM SIZED CAPACITOR, 2.5 L TOTAL MANIFOLD VOLUME

experiment.

The entire system was built on a custom cart on four casters. The experiment needed to moved outside for operation due to noxious exhaust fumes and needed to be stored and operated on in the laboratory so that the sensors would not get damaged by environmental factors.

RESULTS AND DISCUSSION

The goal of the experiment was to measure the effect of capacitor volume on the density of the intake air and the peak power output of the engine. Seven different manifold volumes were built. The experiment was run outside in order to avoid releasing noxious gas indoors. For each capacitor volume, two

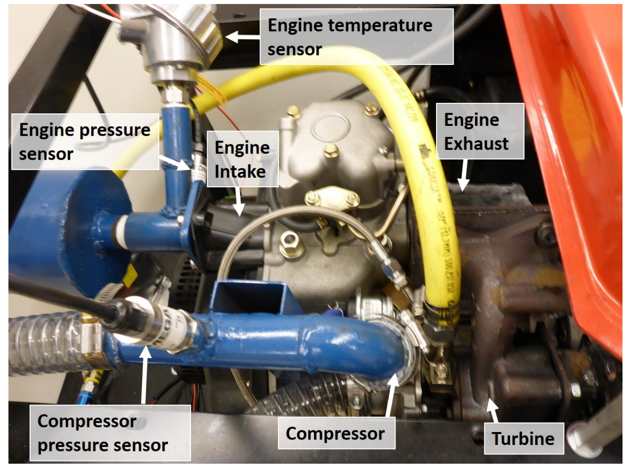

FIGURE 9. NEW MANIFOLD SYSTEM DESIGNED AROUND THE TURBOCHARGER

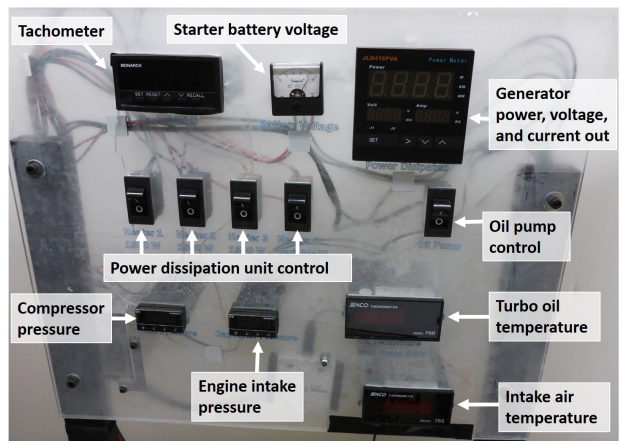

FIGURE 10. CONTROL AND MONITORING PANEL FOR THE DYNAMOMETER

experiments were run. The cold peak power test measured the peak power of the engine after cold start. The hot peak power test measured the maximum peak power that could be sustained by running the engine at increasing loads for minutes at a time until the engine stalled. Density gain in the air capacitor was also measured in these tests using the pressure and temperature sensors.

Density gain is important because it indicates how well the turbocharger is working and should be the same as peak power gain on the first order. It is calculated from the intake temperature and pressure using the ideal gas law (Eqn. 13) and is the percent increase of the intake density over the ambient air density (Eqn. 14).

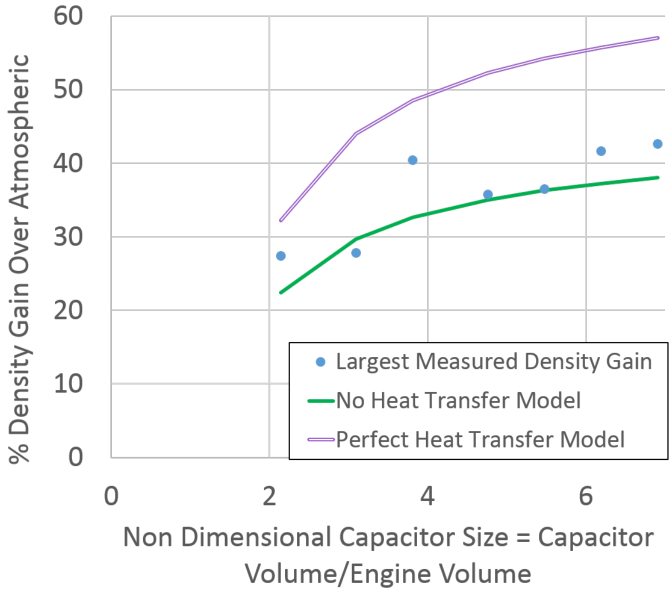

FIGURE 11. MAXIMUM MEASURED INTAKE DENSITY WITH DIFFERENT SIZED MANIFOLDS COMPARED TO THE FULL INTAKE MODEL

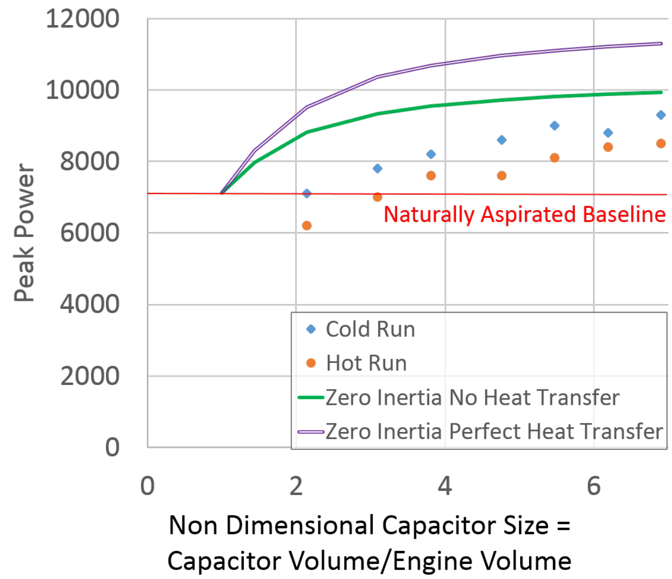

FIGURE 12. MAXIMUM MEASURED POWER GAIN FOR BOTH THE HOT AND COLD TESTS COMPARED TO THE FULL INTAKE MODEL

$$IntakeDensity = \frac{Pressure}{TemperatureXSpecificGasConstant} \quad (13)$$

$$PercentDensityGain = (\frac{MeasuredDensity}{AmbientDensity} - 1)X100 \quad (14)$$

Figure 11 shows the maximum measured density gain for different sized capacitors. The results show a trend that is predicted by the model. As the capacitor volume increases so does the intake density gain. With the largest sized capacitor density gains of over forty percent were observed. In addition to this the density gain falls between the two bounds that the model predicts. Note that because the measurement was taken at less than peak power (due to large pressure fluctuations in the manifold at peak power), the measured peak density is probably less than the actual peak density, which should be the density at peak power.

The key factor that determines the economic feasibility of the system is the peak power gains achieved by turbocharging. Cold and hot peak power were measured for seven different intake manifold volumes and the naturally aspirated case. The results compared to the model are plotted in Figure 12. The power model uses the results of the density gain model and assumes that power gain is proportional to density gain to the first order [10]. Peak power increases of up to twenty-nine percent were observed for the cold case and up to eighteen percent for the hot case. The system had the same trend that the zero inertia temperature adjusted model predicted. As capacitor volume increased, peak power increased. There was also a diminishing marginal return for increasing peak power past a certain point.

The results of this experiment confirm our two main hypotheses. First, it is possible to turbocharge a four stroke single cylinder engine using a large volume intake manifold. Second, the capacitor volume has a key effect on the performance of the engine. It was also found that the model did a reasonable job of predicting peak density gain. However, the peak power gain did not match our model and did not correspond to the density gain to the first order. There were a few possible sources of error that could have contributed to the experimental results not matching the theory exactly. Three primary sources of error were identified.

The first possible source of error was that the ambient conditions were not consistent since tests were run outdoors on different days. The ambient density of the air during the tests could vary by as much as five percent. It is possible to adjust for ambient density to the first order using Eq. 15. The results, after adjusting for ambient temperatures, are shown in Fig. 13. Adjusted peak power increases of up to thirty three percent were observed for the cold case and up to twenty three percent for the hot case. The adjusted results are closer to, but still noticeably less than the predicted power gain.

$$PowerAdjusted = Power\frac{AmbientDensityPowerTest}{AmbientDensityBaselineTest} \quad (15)$$

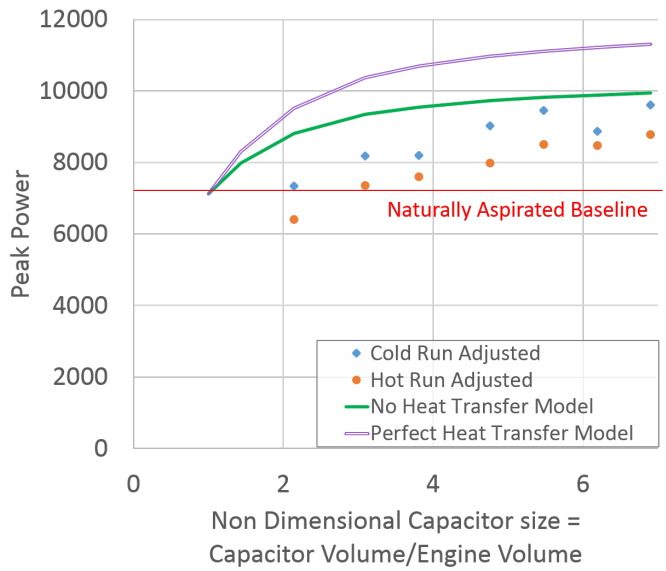

FIGURE 13. MAXIMUM MEASURED POWER GAIN FOR BOTH THE HOT AND COLD TESTS ADJUSTED FOR ATMOSPHERIC CONDITIONS COMPARED TO THE FULL INTAKE MODEL

The second possible source of error was that the theoretical model did not take into account exhaust pressure differential (the difference between intake and exhaust pressure). This would result in increased pumping losses within the engine. It was observed that for all cases the exhaust pressure differential is noticeably larger in the turbocharged case than it is in the naturally aspirated case. This could account for part of the mismatch between the peak power gains and density gains.

A third possible source of error was air leakage. The passage that led from the custom built intake manifold to the intake valves was the same one that the engine came with and was not modified in any way. Since this engine was designed to be naturally aspirated, it was not designed to be under significant positive pressure. This led to leakage in this passage that was significant enough that the operator was able to observe it. This leakage would result in a density reduction of the air going into the engine cylinder, which would cause a reduction in peak power.

CONCLUSION

The design of an experiment to test a method for turbocharging four stroke single cylinder, internal combustion, engines and the results of the experiment are discusses in this paper. The method proposed uses an air capacitor, in the form of a large volume intake manifold, to buffer the inconsistent flow of air from the turbocharger. A typical developing world engine was chosen and was equipped with a turbocharger. A series of sensors were attached to the engine to measure pressure, temperature, and power output. The engine was run naturally aspirated and turbocharged with seven different sized intake manifolds. Using this experimental setup tests were conducted that showed that a turbocharger could be fitted to a single cylinder engine using an air capacitor to substantially increase intake air density and the peak power of the engine. It was found that peak power output increases with manifold volume and that peak power increased by as much as twenty nine percent with the largest sized manifold (approximately seven times engine volume).

This is a significant increase in power and it proves that this method for turbocharging single cylinder engines works. However, it is less than the model predicted. This is probably due to back pressure effects that were not accounted for and the fact that the engine was not designed for positive pressure in its internal intake manifold which resulted in air leaking out. The other key takeaway from the model and literature [1] was that the temperature increase due to compression had a significant effect on performance, indicating that the system would benefit greatly from intercooling.

The technology presented in this paper could create a broad impact on equipment such as tractors, light vehicles, generators, and water pumps increasing their specific power per unit cost and thus making them economical for new users. The next step in this study is to build a more advanced experiment that will allow for measurement of fuel economy, transient effects, and emissions impact.

ACKNOWLEDGMENT

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