SOURCES OF HEAT REJECTION IN A HDDI DIESEL ENGINE AND METHODS TO IMPROVE THERMAL EFFICIENCY

by

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LIST OF ABBREVIATIONS

HDDI - Heavy Duty Direct Injected

BTE - Brake Thermal Efficiency

GIMEP - Gross Indicated Mean Effective Pressure

THR - Total Heat Rejection

EPA - Environmental Protection Agency

FMEP - Frictional Mean Effective Pressure

TTBC – Thick Thermal Barrier Coating

GLOSSARY

Heavy Duty Diesel Engine - A diesel engine that is designed to operate in a class 7 or class 8 on-highway truck. (Heavy-Duty Truck Engines, 2018)

ISO 9001 - International Organization for Standardization classification for a company's quality management system. (All about ISO, 2018)

R-Value - An insulating material's resistance to conductive heat flow is measured or rated in terms of its thermal resistance or R-value -- the higher the R-value, the greater the insulating effectiveness. (DOE, 2018)

ABSTRACT

In the realm of class 8 trucking, fuel economy and emissions compliance are becoming the driving force for development of new heavy-duty direct injected (HDDI) diesel engine technologies. Current production engines in this class convert around 40% of the fuels energy into usable work while the unused potential transfers to the environment as excess heat energy. Current OEMs are working toward decreasing this heat loss and improve engine efficiency and emissions. Quantifying the energy lost by component and system highlights the areas that demand the most attention. By studying test cell data of heat rejection on a production Cummins ISX engine and using the data to calibrate an engine model for the simulation software GT-Suite, heat rejection values and the components which transfer the energy are exposed. The simulation software provides energy transfer by both system and component type. The results reveal that 10% of engine total heat rejection (THR) is transferred through the cylinder wall to the engine coolant system. When the heat imparted on the cylinder wall is broken up by component, the piston rings contribute nearly as much heat into the liner as the combustion gas.

CHAPTER 1. INTRODUCTION

Heavy duty direct injected (HDDI) diesel engines reject up to 40% of the fuel's energy as heat to the environment (Hountalas, Mavropoulos, Katsanos, & Knecht, 2012). Understanding the sources of heat rejection, and quantifying the results, allows engineers to focus efforts on components with the greatest efficiency gains. A heavy duty direct injected (HDDI) diesel engine works by converting chemical energy into work. The conversion occurs by combusting the fuel and using the heat created to push the piston down, rotating the crankshaft. There are several factors to consider when optimizing overall engine efficiency. This paper considers brake thermal efficiency (BTE), gross indicated mean effective pressure (GIMEP) and total heat rejection (THR). These are discussed in further detail in a later section. Currently in the heavy-duty market, engines are averaging 45% BTE. The higher the THR on an engine, the lower the BTE and higher the fuel consumption.

Lowering the heat rejection of an engine has the greatest impact on an overall BTE. The energy lost as heat is wasted fuel and untapped power. By decreasing the amount of heat rejected to the environment brake specific fuel consumption (BSFC) decreases and BTE increases. With the increase in BTE and decrease in BSFC, fuel consumption decreases, and engines produce less greenhouse gas emissions per mile driven. Reducing CO2 emissions aligns with the NAE's list of grand engineering challenges which include methods for carbon sequestration (NAE, 2018). Lowering the output of CO2 aids the efforts of carbon sequestration by lowering the concentration in the atmosphere.

Understanding the sources and the total amount of heat rejected by individual components yields different results for each engine type. The engine architecture studied was a Cummins on highway heavy duty diesel engine with a liquid cooled turbocharger housing.

Engine architecture was studied with industry standardized software, analytically, as well as data measured from a functioning engine in a test cell. Due to the time constraint of this project and the cost associated with running a test cell, the real-world data was historical data and has been normalized to protect any Cummins confidential information. The normalization was accomplished by dividing the raw data by the mean, and all data presented as a percentage of THR and percentage of BTE. Components not measured are left out as to not reveal true THR and BTE values.

1.1 Research Problem Statement

Heavy duty direct injected (HDDI) diesel engines reject up to 40% of the fuel's energy as heat to the environment (Hountalas, Mavropoulos, Katsanos, & Knecht, 2012). Understanding the sources of heat rejection, and quantifying the results, allows engineers to focus efforts on components with the greatest efficiency gains (Penny & Jacobs, 2015). Increasing an engine's thermal efficiency reduces the global production of greenhouse gas CO2 emissions aiding the efforts of the engineering challenge of carbon sequestration (NAE, 2018). Heat rejection of an engine was measured through both mechanical measurements on an operating system as well as through computational analysis.

CHAPTER 2. REVIEW OF LITERATURE

Following a review of literature regarding lowering total heat rejection the methods used are either to increase combustion efficiency, or to insulate components reducing the heat transfer to the coolant system. The predominant method being application of thermal barrier coating of in cylinder components such as the valves, cylinder head, cylinder walls and piston. The insulation of these components consists of a ceramic based compound applied as a slurry and machined to final dimensions. These coatings have a designated "R" value, or the insulation value per unit of thickness, meaning the thickness of the coating determines how much higher the in-cylinder temperatures are comparative to uncoated components. "Higher heat transfer to the combustion chamber walls will lower the average combustion gas temperature and pressure, and reduce the work per cycle transferred to the piston" (Heywood, 1988). The idea of keeping the cylinder environment at an increased temperature serves two additional purposes, "to reduce the size of coolant system & to increase the exhaust energy available for turbo charging and thereby increasing power and efficiency" (Kumar, Annamalai, Parhakar, & Banugopan, 2010). Increasing the in-cylinder temperature also aids in complete combustion of the fuel source which also drives efficiency, but with a tradeoff. "Higher gas temperatures are supposed to reduce the concentration of incomplete combustion at the expense of increase in nitric oxide" (Kumar, Annamalai, Parhakar, & Banugopan, 2010). A study of a single cylinder engine operating within the same boundary conditions with both thermal barrier coating and uncoated was conducted. The coating consisted of mullite, which is made up of aluminum oxide and silicone oxide. The coating was applied to a thickness of 0.5mm on the piston face, cylinder head face and valves. The results revealed that the coated, or LHR engine, saw "as much as 20% increasing on NOx emissions for LHR engine compared to conventional engine at full load" (Shrirao, Shaikh, Zafaruddin, & Pawar, 2012). For model year 2019, the EPA has regulations on the amount of oxides of nitrogen (NOx) that can be produced by an on highway internal combustion engine. These regulations continue to become more stringent as the health and environmental issues surrounding these gasses are still being studied. Many Heavy Duty Direct Injected diesel engine manufacturers are already working towards reducing NOx emissions regardless of potential governmental regulations. Engine aftertreatment catalysts are often manufactured similar to how thermal barrier coatings are applied. The addition of precious metals allows the catalyst to react with the air/fuel mixture. This concept can be applied to the coatings used internally on the engine components. The metals added to the slurry would "allow the ceramic thermal barrier coating material to catalytically react the fuel-air mixture at a higher rate than would the base compound without the ionic substitutions" (Kulkarni, Campbell, & Subramanian, 2009). Internal combustion engines are complex systems in which altering one component affects the rest of the system. By changing the combustion temperature and lowering the transfer of heat to the cylinder walls, the turbocharger has more heat energy available for extraction.

Another method to reduce the amount of heat transfer through cylinder walls is to reduce the temperature delta between the cylinder wall and the combustion chamber. Elevated Engine Coolant Temperature (ECT), is representative of the same theory mentioned before, allowing the cylinder to operate in a higher temperature environment to promote complete combustion of the fuel source. One study demonstrated "results indicate that more than 40% of the input diesel fuel energy is converted to net indicated work, about 1/3 of the energy is rejected to the exhaust gases and the rest is transferred as thermal energy through the combustion chamber" (Li, Caton, &

Jacobs, 2016). Increasing the ECT has shown a decrease in frictional losses in internal combustion (IC) engines. “The operating temperature of the internal combustion engine, i.e. temperatures of the components and the oil and cooling, influence the friction. The reasons for this are, first the change in viscosity of the lubricant and, second, the change in the clearances in the various friction pairs” (Stanislav, Pavel, Ondrej, & Robert, 2013). The reduction of frictional losses can be attributed to the viscosity of the engine lubricant fluid, and these frictional losses can also be diminished by using a lower viscosity engine oil. The methodology was the “LHR operating condition is implemented by increasing the engine coolant temperature (ECT). Experimentally, the engine is overcooled to low ECTs and then increased to 100 °C to get trend-wise behavior without exceeding safe ECTs” (Li, Caton, & Jacobs, 2016). The results of the study are nothing unexpected. “Increasing ECT yields reduction in cylinder heat transfer but almost equivalent increase in the exhaust losses”. (Li, Caton, & Jacobs, 2016) “The brake fuel conversion efficiency, however, shows to be significantly improved at the studied higher ECT conditions where the substantial reductions in frictional losses may occur” (Li, Caton, & Jacobs, 2016). Elevated ECT’s not only lower frictional losses within the engine, they promote complete combustion and a reduction of CO and HC emissions which are both considered greenhouse gasses.

The elevated exhaust heat rejection due to insulated cylinder components can still be harnessed and utilized for useful work. An engine equipped with thermal barrier coatings saw “as much as 22% increasing on exhaust gas temperature for LHR engine compared to conventional engine” (Shrirao, Shaikh, Zafaruddin, & Pawar, 2012). The concept of waste-heat recovery is nothing new, that “recovering excess or wasted heat from a primary thermodynamic process via a bottoming cycle” (Teng, 2010). To utilize the energy through the exhaust system efficiently, one would employ a waste heat recovery (WHR) system in the EGR cooler circuit. Using an organic working fluid with a lower boiling point than water allows the fluid to become a super-heated gas, that can drive the wheel of a turbine connected to an electrical generator. A WHR unit as described utilizes the Rankine cycle to extract work from the heat that would have otherwise been waste heat. While still within the vast topic of lowering heat rejection, heat leaving the engine as exhaust can still be utilized. The turbocharger that provides combustion air to the cylinders, requires that a given amount of heat be available to use to perform the mechanical work of compressing the combustion air. The amount of heat required depends on engine air flow demands as well as turbocharger efficiency. The delta across the turbine wheel correlates to the turbo machine efficiency. The WHR unit turbine also utilizes the delta temperature to perform its mechanical work. The study by Teng "demonstrated turbine power recovered from this system represents a 3-5% improvement in engine fuel consumption" (Teng, 2010). Results from the study only tell part of the story. When one considers the additional benefit to the powertrain system in terms of reduced cooling system requirements, overall vehicle efficiency increases proportionate to the cooling system efficiency. Cooling fans and water pumps can be downsized which reduces accessory drive parasitic losses" (Teng, 2010). By applying the concepts of lowering in cylinder heat transfer to increase the available heat in the exhaust, WHR units operate more efficiently to convert this heat into work.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Research Methodology

Encompassing both software analysis and functioning engine test cell data was used to confirm the concept. The software section was completed with a GT power analysis tool prescribed to a 137mm bore and a 169mm stroke. The software suite GT power has established itself as an industry standard for computational fluid dynamics modeling. The test cell data was collected from a 6-cylinder class 8 truck engine with a liquid cooled turbocharger housing. A class 8 truck as defined by the United States Department of Transportation is a vehicle with a maximum gross recommended vehicle weight greater than 33,001lbs (Vehicle Weight Classes & Categories, 2018). The data used was historical data collected in the last three years from the Cummins Technical Center and was normalized to protect any confidential information. Due to the time and cost of running a test cell with measurement equipment, there was only one engine sampled. The data was comprised of varying engine operating conditions such as idle, torque peak as well as rated horsepower and compared to the software analysis of the same conditions for validation.

3.2 Research Instruments

Gamma Technology's GT-SUITE contains the software GT-Power that was used for analysis. The software package "GT-SUITE is the industry-leading simulation tool with capabilities and libraries aimed at a wide variety of applications and industries" (GT-SUITE Overview, 2018). GT-power analysis has proven worthy, providing the inputs are correct. To validate the analysis, data from a functioning engine was used to confirm the data. The measurement devices on the engine are AVL high speed data acquisition software with AVL cylinder pressure transducers. Temperatures are measured using various sizes of Omega thermocouples depending on the location. Fuel flow and Air flow are measured using Coriolis type density corrected mass flow meters. All the measurement devices and recorders fall under ISO 9001 certification.

3.3 Data Gathering

The physical engine data has been collected and was used to calibrate the software-based analysis. The data from the GT power model was captured both in graphs as well as screenshots of the analysis in progress. The GT power software generates pre-programmed plots to aid in illustrating the results. The process of running an engine model through GT power was a detailed process. For this research, A Cummins employee regarded as an expert in the subject matter oversaw the modeling.

3.4 Presentation of Data

The data collected was presented in both graphical form as well as figures. Thermal mapping images were shown to highlight the areas with the greatest THR and thus greatest areas for improvement. There are screenshots of the software analysis and 3D thermal mapping graphical data to illustrate the findings. The test cell gathered data was processed and normalized using MatLab to strip units and normalize values. The normalization was done to protect Cummins confidential data. The test cell data was entered in GT-Power, the analysis tool, for means of calibration.

3.5 Return on Investment

The value proposition to Cummins by performing this quantification of heat rejection sources, is advancement of future technologies leading to increased market share and customer brand recognition. There is no finite number as to the market response to producing more fuel-efficient engines than the competition. The competitive market for class 8 trucks translates to a more fuel-efficient truck that can travel longer distances between fuel stops being more desirable than the competition. The benefits of producing cleaner running engines include obtaining future Department of Energy (DOE) research contracts, increased brand recognition and readiness for future emissions regulations. The environmental benefits of creating more fuel-efficient and cleaner running engines are a decreased dependency on fossil fuels to transport freight. Also, the reduction of greenhouse gas emissions such as CO2 and particulate matter. These benefits aid not only Cummins, but trucking companies around the world and the engineers working toward carbon sequestration.

Presenting the data that numerically highlights the areas with the greatest heat rejection, allows engineers to focus improvement efforts to the areas with the greatest potential for improvement. Quantifying the areas with the greatest potential for benefit to enable improvements in THR and BTE to occur quicker. Addressing the areas discovered to be the highest contributors to heat rejection leads to more efficient HDDI engines by Cummins, reaping a greater market share, and ultimately providing cleaner more efficient on highway class 8 truck engines.

3.6 Summary

The data collected from both an engine test cell and GT-Power simulation software provide evidence to purchase and test proof of concept parts. The data collected from the test cell was collected with ISO 9001 certified equipment, and was used as a baseline to compare future improvements against. The data collected through the GT-Power simulation software was faster and cheaper to obtain than on engine testing. The cost of running a test cell through a third party exceeds $10,000 per week, and does not include the cost of prototype parts. The GT-Power software is the industry standard for engine simulation, and simulates weeks of testing in a matter of hours. The data output of the software was both graphical and numerical, simulating surface temperatures of engine components as well as heat transfer rates of individual components. The data generated drives improvement efforts toward the areas of the highest heat rejection, which allows Cummins Inc. to improve class 8 on-highway trucking.

CHAPTER 4. RESULTS

The following results quantifying the sources of heat rejection in a HDDI diesel engine, specifically a Cummins ISX. This enables engineers within Cummins to view each component that contributes to THR and make improvements to components with the greatest impact. Measurements were taken of coolant inlet and outlet temperatures of a running engine in a test cell. The EGR cooler coolant delta temperature and turbine inlet and outlet temperatures were also measured and used to calibrate the model for the simulation software. Once the boundary conditions were established in the GT-ISE software, a simulation was ran using GT-cool at different operating conditions along the torque curve of the engine. The GT-Power simulation was run with certain variables such as ambient air temperature and airflow across the engine block to be selected by the software. The software selects random feasible values for these variables to create a more accurate simulation of different driving environments the engine sees. The charge air cooler (CAC) and radiator are not modeled as predictive heat exchangers like the EGR cooler. The modeling on the radiator and CAC are derived from the desired outlet temperature and the expected pressure drop across the heat exchanger. These two components are often not designed by the engine manufacturer and are left to the discretion of the chassis manufacturer. The simulation was run a total of twelve times with these variables being changed and the results averaged. The results of the calibrated simulation are assembled in this chapter and are discussed below.

GT-Power software uses a 3D model of the engine structure to perform the analysis. The simulation results also allow for thermal mapping to be performed simultaneously with the performance analysis. The in-cylinder components with the highest heat transfer rates are the exhaust valves, exhaust ports, piston, cylinder wall and head. The analytical software provides visual representations of the thermal mapping with much greater resolution than what can be achieved in an instrumented component in a test cell. As shown in Figure 4.1 below, the exhaust valves reach upward of 900 K as the exhaust gas temperature and velocity impart significantly more heat than the valve can dissipate through its small contact with the valve seat in the head. The effect of this heat being transferred to the head can still be seen on the cylinder head view as the area around the exhaust ports maintains a higher temperature than the rest of the combustion face despite coolant flow on the back side of the face.

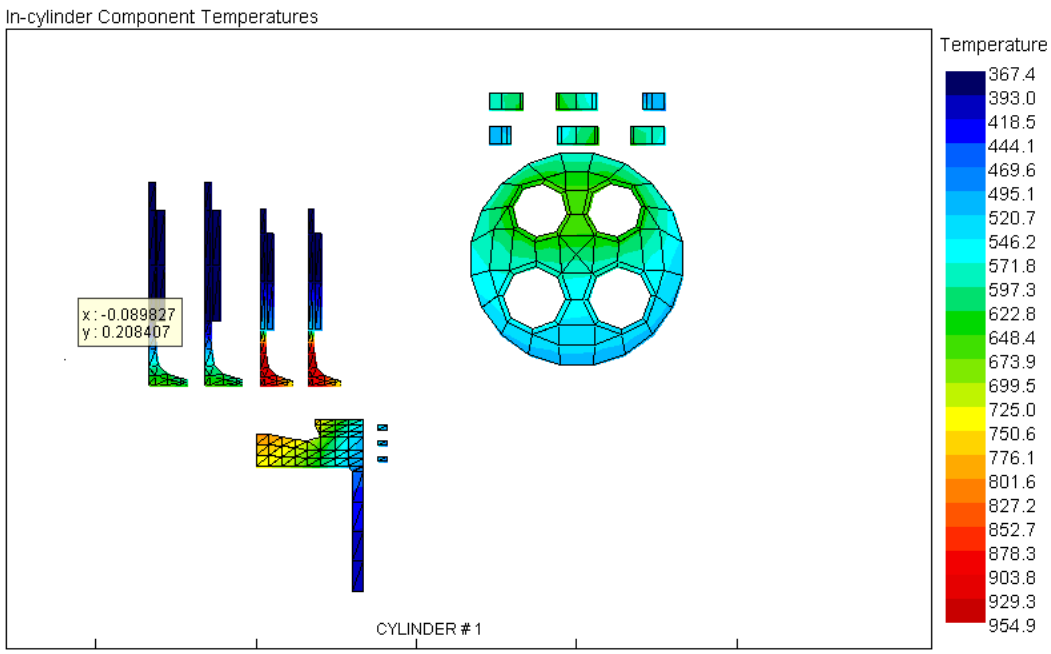

Figure 4.1 In-Cylinder Component Temperatures

There are interesting dynamics exposed to the cylinder head combustion face. The face itself has exposure to the combustion flame front, and the valve seats and ports are exposed to extreme temperature gas flow at high velocity. The exhaust port and valve seat can be exposed to gas temperatures exceeding 3000 K, and the intake valve seats and ports can be as low as 300 K.

Figure 4.2 illustrates the drastic temperature differential across the combustion face due to the differing charge flow and exhaust flow properties.

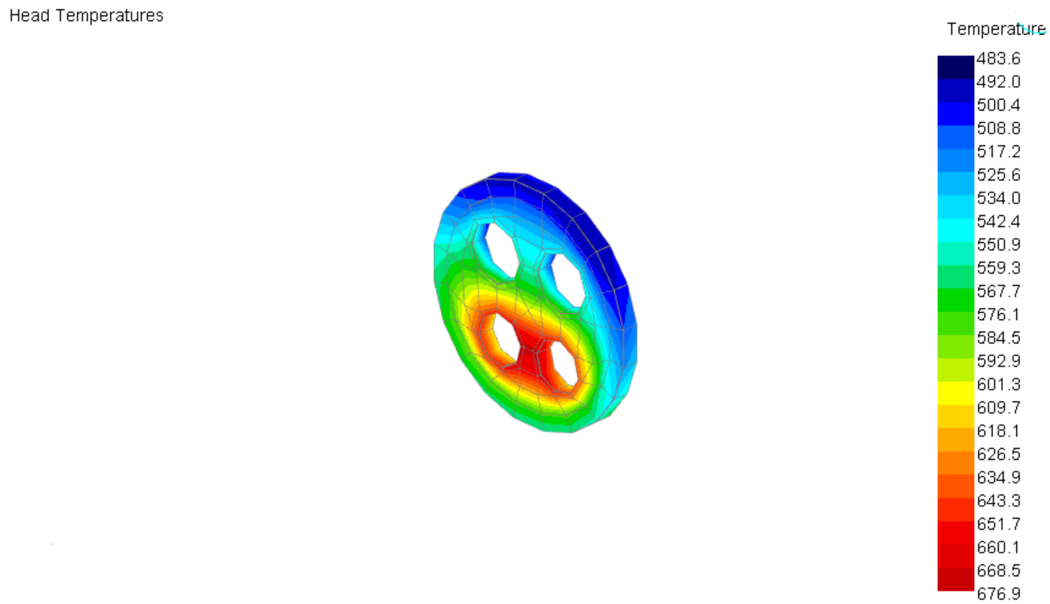

Figure 4.2 Head Temperatures

The drastic temperature differential across the combustion chamber effects the cylinder walls as well. The turbulence of the burned mixture exiting through the exhaust valves on one side of the combustion chamber impart localized heat into the liner. As you can see in Figure 4.3 on page 22, the cylinder liner which was surrounded by a coolant jacket does not maintain a consistent temperature. The GT-Power software analysis of these components produces a detailed thermal map image that determines thermocouple location on test engines. The data from the test cell was then used to validate the model. In Figure 4.3, the delta temperature of the cylinder liner from intake to exhaust side was evident.

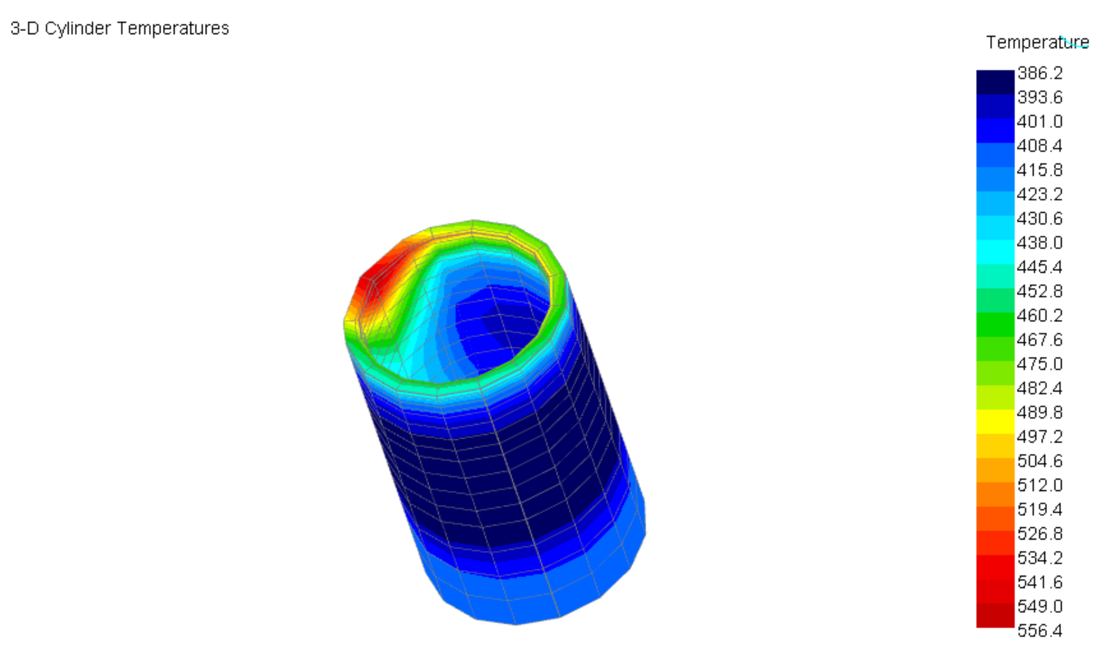

Figure 4.3 3-D Cylinder Liner Temperatures

Once the temperature was calculated in the software, heat rejection can now start to be calculated. Taking the thermal mass of a component and the contact area with other components and their relative temperature was how heat transfer rates were calculated. The in-cylinder heat transfer rates are shown for the piston, rings, cylinder wall, head and valves in Figure 4.4 on page 21. Quantification of the thermal energy from the combustion event and the heat energy flow paths are illustrated and annotated in Figure 4.4. The direction of the arrows indicates the direction of heat influx while the numbers indicate the amount of heat energy.

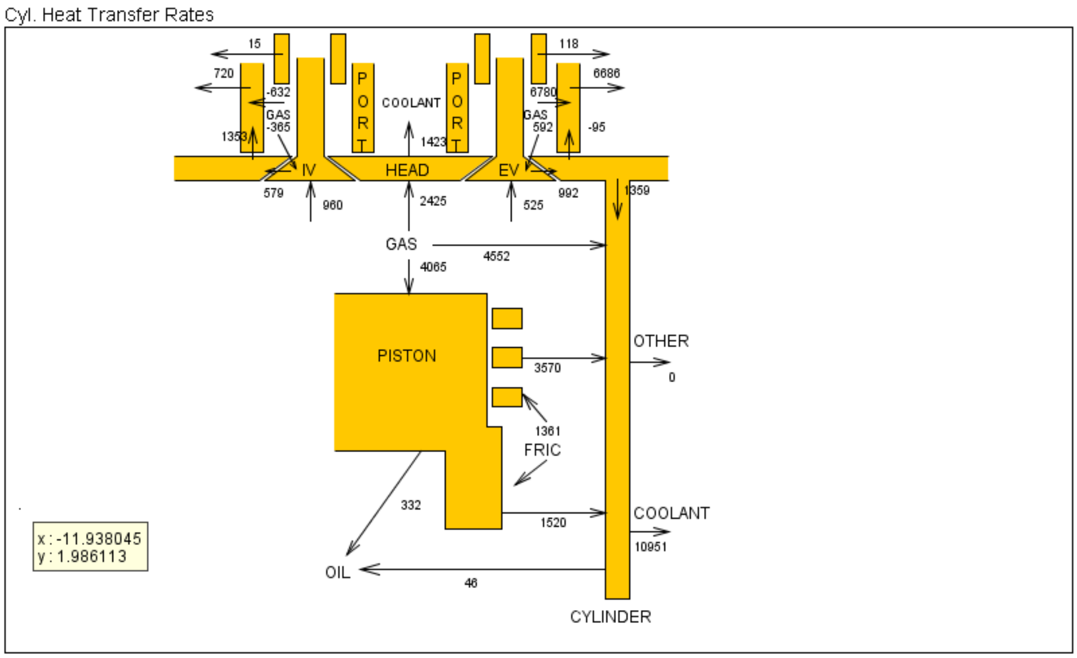

Figure 4.4 Cylinder Heat Transfer Rates

The values shown above in Figure 4.4 are also from engine operating point #1. The GT-Power simulation software ran four distinct operating conditions three times each, varying environmental inputs, for a total of twelve data sets. For the protection of Cummins proprietary data, the operating condition specifics were not revealed. The values illustrated in Figure 4.4 are listed numerically below in Figure 4.5 along with the data for the other operating conditions.

RLT Name ☑ *Hide Unstored RLT Variables*	Unit	Case #1	Case #2	Case #3	Case #4
Heat Transfer Gas to Head		2425.0742	2416.771	1856.3473	1152.13
Heat Transfer Gas to Piston		4065.0715	4092.2002	3316.683	2195.1318
Heat Transfer Gas to Ports/Guides		6148.2256	4996.3413	2518.6536	658.6163
Heat Transfer Gas to Valves		1711.5509	1637.9653	1257.4696	818.0158
Heat Transfer Gas to Cylinder Liner		4552.2983	4101.341	2666.3687	1026.3094
Heat Transfer Coolant to Head		-1423.0792	-1280.0234	-803.2096	-348.33313
Heat Transfer Coolant to Cylinder Liner		-10951.002	-10315.026	-7539.87	-4238.5146
Heat Transfer Coolant to Ports/Guides		-7539.3853	-6440.0703	-3705.6458	-1440.8269

Figure 4.5 Heat Transfer Values

Total heat rejection was broken up by systems including Coolant, EGR, Oil and CAC. These values are what allowed the completion of the quantification analysis to determine which system can achieve the greatest improvement in heat rejection. The data shown in Figure 4.6 illustrates the total for each of the systems. Notice that the value for Case 1,2 and 3 have “0” for the EGR system. The value of “0” was due to these operating points not having EGR flow. The GT-Power simulation data shows that throughout the different operating conditions the coolant system was continually the largest contributor of heat transfer. The reason the coolant system was the largest contributor to heat transfer was due to the amount of engine components that maintain temperature by transferring heat to the cooling system. The key take-away was that the coolant system accounts for nearly 80% of the engine heat rejection across the operating map.

RLT Name Hide Unstored RLT Variables	Unit	Case #1	Case #2	Case #3	Case #4
Favorites					
HR-Coolant-block		76846.914	70768.51	46958.234	22791.432
HR-Coolant-EGR		0.0	0.0	0.0	1393.4344
HR-Oil		2154.0325	2901.4485	3021.1487	1471.3809
HR-CAC		17485.633	14794.421	8908.451	906.5708

Figure 4.6 Heat Rejection Values

The measurements that were taken on the test cell engine were verified to align with their corresponding values from the simulation. The simulation data can now be used to identify specific components with the largest potential improvement. Adding a thermal coating to a component changes the components heat transfer rate, which can be changed in the model and the simulation ran again. Using the simulation software to examine the effects of a thermal barrier coating reduces the cost of acquiring prototype parts and running them in a test cell. The data from the simulation also develops a thermal survey map of the components allowing engineering staff to confidently identify locations measurements need to be taken. Detecting precise locations to place thermocouples in a test cell environment further reduces the cost of research and development within Cummins engineering.

CHAPTER 5. SUMMARY AND CONCLUSIONS

5.1 Summary

Rationalizing the test cell data and the simulation data yields component contribution to THR. By identifying components that are the largest contributors of heat rejection, efforts of improvements are focused on the largest contributors. Reducing the THR of an HDDI diesel engine lowers fuel consumption, improves efficiency, and reduces the carbon footprint of class 8 on-highway trucks. The reduction of carbon emissions produced per mile driven aids the efforts of carbon sequestration and aligns with the NAE's grand engineering challenge.

The largest contributor of heat rejection in the engine tested was heat transferred from the cylinder wall to the engine coolant. There are several sources of heat influx to the cylinder wall including, combustion gas, piston ring conduction, piston ring friction, piston skirt friction and oil conduction. The combustion gas to cylinder wall accounts for nearly half of the heat induced into the coolant system via the cylinder wall. Piston ring conduction accounts for nearly a third of the heat transfer on the cylinder wall. The total heat energy transferred through the cylinder wall to the coolant system accounts for almost ten percent of the total engine heat rejection.

The air handling system which includes the engine coolant cooled turbocharger housing and the charge air cooler account for nearly 20% of the THR. Compressing combustion air generates heat that must be removed before entering the intake manifold. The result of not cooling the combustion air leads to higher in-cylinder temperatures and an increase in toxic NOx production. The turbocharger housing exposure to exhaust gas with temperatures more than 400°C and friction from a shaft spinning over 100,000rpm . The heat needs to be removed from the turbocharger by the coolant system to prevent the lubricating oil from coking.

5.2 Conclusions

The review of literature illustrated common methods of reducing THR. The software analysis poses the cylinder wall to coolant interface as the largest contributor to engine heat rejection. The key data from this research shows that nearly 20% of the energy lost through the cooling system was passed through the cylinder wall. The energy lost through the cylinder wall can be contained in the cylinder and more effectively extracted by the piston.

Containing this energy in the cylinder leads to greater engine thermal efficiency. Thermal efficiency consists of the effective extraction of heat energy in the production of work. The review of literature uncovered the amount of research done regarding thermal barrier coatings. A thermal barrier coating applied to the bottom half of a cylinder liner around the outside lowers the heat transfer of the combustion gas to the liner. The bottom half of a cylinder liner was exposed to lower temperature gas relative to the upper half of the liner and has a lower exposure time. Cooling of the liner near the area of top ring reversal where the rings are susceptible to over-heating and end butting proves critical. Holding more heat in the liner material near the bottom reduces the delta temperature and reduce heat loss. The reduction in heat loss equates to higher in-cylinder temps and therefore pressures. The increased combustion gas temperature and pressure near BDC enables more energy to be extracted from the combustion event and increased temperature and pressure to drive the turbocharger.

5.3 Recommendations

The data presented highlights the areas of an HDDI diesel engine which are the highest contributors of heat rejection. Recommended further investigation is to calibrate the 3D model to be representative of parts coated with thermal barrier coatings. Careful attention needs to be paid to the interactions between components during the simulation. Retaining excess heat within the engine structure can lead to shortened service intervals or even part failure. The engine component interaction with parts transferring less heat becomes the new unknown. Full simulation analysis needs to be performed before testing on a functional engine that has adequate measurement equipment to detect changes. A further recommendation is to apply the concept of a Thick Thermal Barrier Coating (TTBC) containing catalyzing ionic compounds to determine the effects on emissions reductions.

LIST OF REFERENCES

All about ISO. Retrieved (2018, December 1) from International Organization for Standardization: https://www.iso.org/about-us.html

Beardsley, M. B., Socie, D., Redja, E., & Berndt, C. (2006, March 26). Thick Thermal Barrier Coatings (TTBCs) for Low Emission, High Efficiency Diesel Engine Components. *U.S. Department of Energy Office of Scientific and Technical Information*. doi:10.2172/878132

Brinkman, C., Liu, K., Graves, R., & West, B. (1991). Low heat rejection diesel ceramic coupon tests. *International symposium on ceramic materials and components for engines.* Goeteborg.

Energy, D. O. *Energy Saver - Insulation*. Retrieved (2018, December 23) from United Stated Department Of Energy: https://www.energy.gov/energysaver/weatherize/insulation

Gaydos, P., & Dufrane, K. (1993). *Studies of dynamic contact of ceramics and alloys for advanced heat engines. Final report.* Washington, DC: U.S. Department of Energy Office of Scientific and Technical Information. doi:10.2172/10171690

GT-SUITE Overview. Retrieved (2018, December 2) from GTI Software: https://www.gtisoft.com/gt-suite/gt-suite-overview/

Heavy-Duty Truck Engines. Retrieved (2018, November 30) from Cummins Inc.: https://www.cummins.com/engines/heavy-duty-truck

Heywood, J. B. (1988). *Internal Combustion Engine Fundamentals.* New York: McGraw-Hill Publishing Company.

Hopman, U., & Kruiswyk, R. W. (2005). *Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology*. Washington, DC: U.S. Department of Energy Office of Heavy Vehicle Technolgies. doi:10.2172/862432

Hountalas, D., Mavropoulos, G., Katsanos, C., & Knecht, W. (2012). Improvement of bottoming cycle efficiency and heat rejection for HD truck applications by utilization of EGR and CAC heat. *Energy Conversion and Management, Vol 53, Issue 1*, 19-32.

Kulkarni, Anand A., Campbell, Christian X., & Subramanian, Ramesh. *Catalytic thermal barrier coatings*. United States.

Kumar, P. A., Annamalai, K., Parhakar, S., & Banugopan, V. N. (2010, November). Analytical investigations on heat transfer in a low heat rejection DI diesel engine. *Frontiers in Automobile and Mechanical Engineering*, pp. https://ieeexplore-ieee-org.ezproxy.lib.purdue.edu/document/5714844.

Li, T., Caton, J. A., & Jacobs, T. J. (2016, December 15). Energy distributions in a diesel engine using low heat rejection (LHR) concepts. *Energy Conversion and Management*, *130*, pp. 14-24. Retrieved from https://doi.org/10.1016/j.enconman.2016.10.051

NAE. *NAE Grand Challenges for Engineering*. Retrieved (2018, November 1) from Engineering Challenges: http://www.engineeringchallenges.org/challenges.aspx

Olmeda, P., Martin, J., Blanco-Cavero, D., Warey, A., & Domenech, V. (2017). Effect of in-cylinder swirl on engine efficiency and heat rejection in a light-duty diesel engine. *International Journal of Engine Research, 18*(1-2). doi:10.1177/1468087417693078

Penny, M. A., & Jacobs, T. J. (2015). Efficiency improvements with low heat rejection concepts applied to diesel low temperature combustion. *International Journal of Engine Research*.

Pulkrabek, W. W. (2003). *Engineering Fundamentals of the Internal Combustion Engine.* Upper Saddle River: Pearson Prentice Hall.

Rumsey, J. (2005). *Off-Highway Heavy Vehicle Diesel Efficiency Improvement and Emissions Reduction.* U.S. Department of Energy. doi:10.2172/915099

Shrirao, P. N., Shaikh, P. I., Zafaruddin, F., & Pawar, A. (2012, November 12). An Experimental Investigation on Engine Exhaust Emissions of a Low Heat Rejection (Mullite Coated) Single Cylinder Diesel Engine. *Advanced Materials Research, 588-589*, pp. 344-348

Stanislav, B., Pavel, B., Ondrej, D., & Robert, V. (2013, August). Influence of the mean friction pressure on the temp. *Applied Mechanics and Materials, 390*, pp. 350-354. doi:10.4028/www.scientific.net/AMM.390.350

Teng, H. (2010, October 5). Waste heat recovery concept to reduce fuel consumption and heat rejection from a diesel engine. *SAE International Journal of Commercial Vehicles*, 60-68. Retrieved from SAE International Journal of Commercial Vehicles: https://doi.org/10.4271/2010-01-1928

United States. Dept. of Energy. Office of Energy Efficiency Renewable Energy. (2001). *Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology*. Washington, D.C.: Oak Ridge, Tenn.: United States. Dept. of Energy. Office of Energy Efficiency and Renewable Energy; distributed by the Office of Scientific and Technical Information, U.S. Dept. of Energy.

Vehicle Weight Classes & Categories. Retrieved (2018, December 3) from U.S. Department of Energy: https://afdc.energy.gov/data/