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Conceptual design of a small-displacement engine for a high-efficiency experimental vehicle

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-----ABSTRACT-----
This work addresses the design and optimization of a small-displacement internal combustion engine for a competitive experimental vehicle. This competition encourages students to design and construct vehicles with the highest possible energy efficiency. Participating teams compete in various categories; the category of this work aims to cover the greatest possible distance using the equivalent of one liter of fuel. The paper concentrates on key aspects of engine concept development, including the selection of a suitable concept, modification of an existing commercial engine, and the design of a proprietary solution.
KEYWORDS;- *internal combustion engine, optimization, small-displacement, efficiency*

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I. INTRODUCTION

This article addresses the complex development of a highly specialized propulsion unit designed for maximum fuel efficiency. The design philosophy for ultra-light competition vehicles differs significantly from conventional small engine applications. Since this vehicle operates at low loads and speeds with extended coast phases, the optimization priority shifts from maximizing peak power to minimizing mechanical and thermal losses. Consequently, this work focuses on strategies to increase indicated efficiency within the competition's narrowly defined operating constraints. These unique conditions necessitate a departure from conventional engineering approaches and enable the implementation of advanced technical solutions aimed at maximizing thermodynamic efficiency.

II. METHODOLOGY

The main criteria for the design were the minimization of displacement volume, maximization of thermodynamic efficiency, minimization of mechanical losses (friction), low structural weight, feasibility of production in the conditions of FME (Faculty of Mechanical Engineering) TUKE, and the and the potential for further optimization and experimental validation. All designs were created using SolidWorks CAD software. The four-stroke single-cylinder Honda GX35 engine was selected as the base motor. This unit was chosen primarily because its geometry, component availability, and the FME TUKE team's extensive prior experience with the platform provide a reliable baseline for controlled modifications. Furthermore, its compact size and OHC layout make it suitable for the comparative evaluation of porting, thermal insulation, and valvetrain concepts. [1,2]

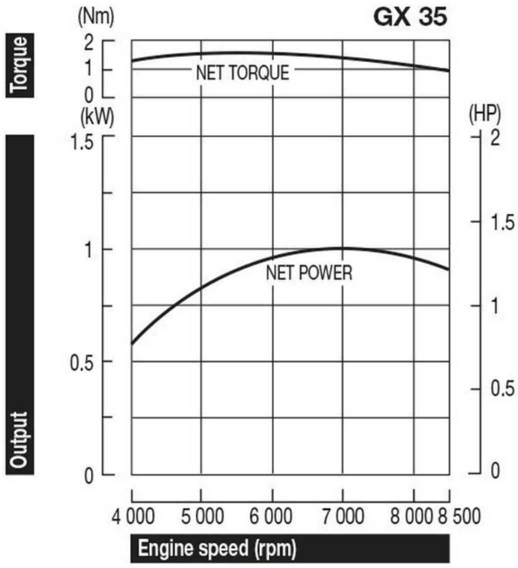

Figure 1 Stock power and torque curve [1]

Table 1 Technical specifications of standard motor [1]

Engine type	4-stroke single cylinder OHC petrol engine
Bore	39 mm
Stroke	30 mm
Displacement	35.8 cm³
Compression ratio	8.0:1
Net power	1.0 kW (1.3 HP) at 7000 rpm
Max. net torque	1.6 Nm at 5500 rpm

Engine disassembly and component preparation

To allow for detailed modifications and the application of special surface treatments, it was first necessary to disassemble the selected engines. This step allowed access to the internal surfaces and channels of the engine for subsequent modifications.

Figure 2 Ignition system

Figure 3 Clutch mechanism

Figure 4 Crankshaft mechanism

Figure 5 Timing and valvetrain

Optimization of intake and exhaust ports

One way to increase the engine's potential efficiency is to refine the geometry of the intake and exhaust ports. The primary objective of this redesign is to improve the discharge coefficient by straightening the flow path and removing restrictive factory casting imperfections. Existing flow studies on small engines demonstrate that the flow coefficient is strongly dependent on valve lift and seat geometry. Based on these findings, the proposed design eliminates sharp edges in the intake tract to theoretically maximize cylinder filling. For low-displacement engines like the Honda GX series, the factory port geometry is often a manufacturing compromise. Therefore, the targeted manual porting aims to correct these deficiencies, yielding improvements in volumetric efficiency especially at the low-to-medium engine speeds crucial for the competition. [2,3]

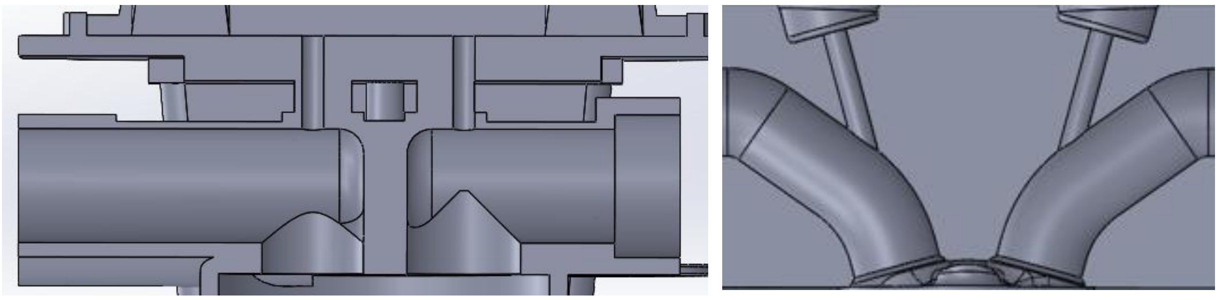

Figure 6 Intake and exhaust ports before (left) and after rework (right)

III. ENGINE CONSTRUCTION DESIGNS

Modified Honda GX35 engine without cooling fins

The key conceptual adjustment involves optimizing the engine's thermal management through a targeted split cooling strategy. Unlike the standard configuration designed for continuous full-load heat dissipation, the modified design removes the air-cooling fins specifically from the cylinder head and the upper section of the cylinder. These surfaces were subsequently covered with ceramic thermal insulation tape. To ensure this adiabatic approach does not compromise volumetric efficiency, a selective insulation strategy was applied. While the combustion chamber and exhaust port are wrapped to retain heat, the intake tract is strictly excluded from this treatment and thermally decoupled using a phenolic spacer. This prevents the incoming air charge from absorbing excessive wall heat, ensuring high air density. However, the cooling fins on the lower crankcase were strictly retained to ensure sufficient heat rejection from the lubricating oil. The design leverages the specific driving strategy of the competition, where the engine operates in short bursts of approximately 10 to 15 seconds, followed by long coasting phases. This intermittent duty cycle prevents the engine from reaching thermal saturation, allowing for a much more aggressive insulation strategy than would be possible in a continuous-duty engine. Building upon the team's prior experience mentioned in the methodology, the engine's thermodynamic baseline was improved using a modified high-compression piston developed and validated in previous vehicle generations. This modification raises the geometric compression ratio from stock 8.0:1 to 12.0:1, compensating for partial-load efficiency losses. Crucially, this high-compression bottom-end assembly is carried over to Variant 2, where it serves as a prerequisite for the effective implementation of the Miller cycle.

Justification for this modification is based on two primary objectives. The first being heat conservation, original design with cooling fins is engineered for maximum heat dissipation during continuous operation. In our case, however, as the engine runs for short cycles, this causes rapid cooling of the engine during long phases of inactivity, leading to lower thermodynamic efficiency and increased frictional losses at each subsequent start. The removal of the fins and the application of a thermo-wrap aim to significantly slow this cooling rate. This approach is based on the concept of the adiabatic (low heat rejection) engine. Reducing heat transfer to the surrounding environment increases the energy contained in the exhaust gases and theoretically improves the cycle's thermal efficiency. Although complete adiabaticity is impossible, using insulating materials helps maintain a higher working fluid temperature, positively impacting combustion efficiency. [4]

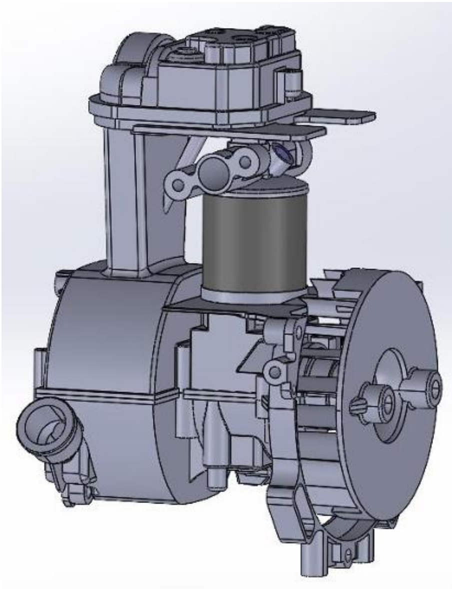

Figure 7 Model of the engine with cooling fins removed and with thermal insulation implemented

Simplified geometry Honda GX35 with a new cylinder head and electromagnetic valve control

Instead of the standard OHC valve train implements a direct electromagnetic valve control system and uses two spark plugs. The primary advantage is the high degree of flexibility in valve timing, allowing for advanced combustion strategies such as the Miller cycle. However, despite its advantages, the concept faces a critical disadvantage in the scalability of existing camless technology. Currently commercially available actuators and research data are primarily derived from automotive-sized engines. In these applications, the power consumption of a single actuator (approximately 40 W at 3000 rpm and up to 90 W at 6000 rpm) represents a negligible fraction of the total output for automobile engines. For a 35cc micro-engine with a peak power of only around 1500 W, this constitutes a significant parasitic load that would drastically reduce the efficiency of the propulsion unit. Furthermore, downsizing standard actuators encounters severe physical scaling limits. An analysis of commercially available miniature solenoids illustrates this technological gap through their force-stroke characteristics. As demonstrated in Figures 8 and 9, while these actuators exhibit their peak force at zero stroke (holding position), their force decays exponentially as the stroke increases. Specifically, the data reveals that at a stroke of approximately 3 mm, the available pull-in force drops drastically below 8 N even when operating at peak power input (10% duty cycle). The critical limitation is therefore the insufficient pull-in force at the maximum air gap. At this required lift initiation point, the available force drops significantly below the level required to open the exhaust valve against the high residual cylinder pressure. Additionally, the maximum stroke of standard industrial components is often restricted, which would severely limit engine breathing compared to the standard lift.

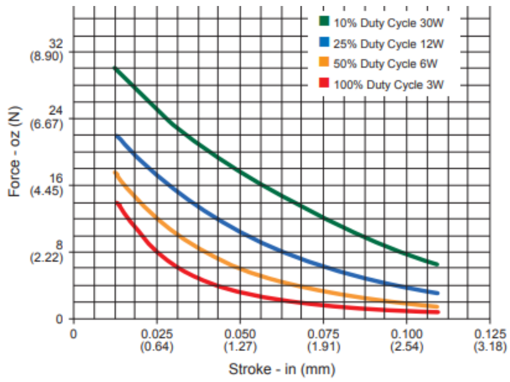

Figure 8 Force-stroke characteristics of the Ledex Size 50 STA Mini Solenoid [9]

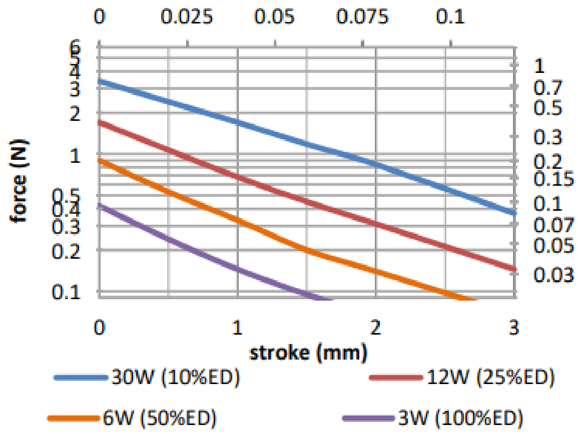

Figure 9 Force-stroke characteristics of the Geeplus tubular solenoid size 133 [8]

Therefore, off-the-shelf components cannot be utilized, and successful implementation requires the development of a highly specialized, custom-designed electromagnetic unit optimized for high force density. However, even with such specialized hardware, the overall power balance remains a critical challenge. In the context of the Shell Eco-marathon competition, where total energy efficiency is quantified using a joulemeter (summing both fuel and electric energy consumption), there is a significant risk that the electrical energy required for the actuators will exceed the mechanical energy saved by eliminating camshaft friction, potentially leading to a net negative efficiency gain. Consequently, the analysis of these characteristics leads to the conclusion that the proposed electromagnetic valvetrain is intended primarily as a research tool for development purposes rather than a practical solution for the immediate competition. Its objective is to experimentally validate advanced cycle strategies and enable precise control of valve timing, providing essential data to support the future development of a fully custom high-efficiency engine. [5-9]

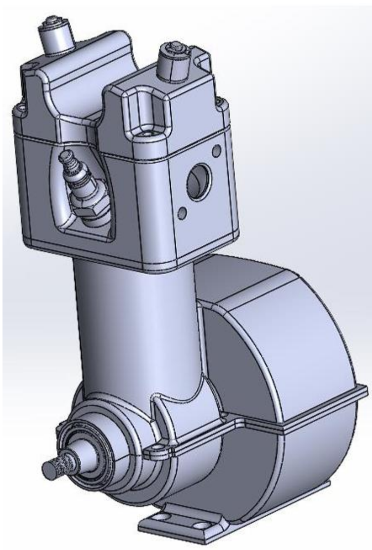

Figure 10 Simplified geometry

New low-displacement engine concept

The third design variant represents a completely new engine architecture developed specifically for the competition's requirements, aiming to surpass the limitations of commercially sold units. The technical specification outlines a single-cylinder, four-stroke engine with a displacement of 30 cm³ with 32,5 mm bore and 36 mm stroke, utilizing AlSi10Mg alloy (standard EN AC-43000) for its construction. The long-stroke architecture was deliberately chosen to minimize the combustion chamber's surface-to-volume ratio, thereby reducing heat transfer losses to the cylinder walls, which is prioritized particularly important at the extremely low engine speeds used in the competition.

The piston area was determined based on the bore diameter using the following equation:

$$Apiston = \frac{\pi D^2}{4} \quad (1)$$

GX35 (39 mm bore 30 mm stroke) - 1194,6 mm^2

New concept (32,5 mm bore to 36 mm stroke) – 829,6 mm^2

The significant downsizing of the bore from 39 mm to 32,5 mm resulted in a 30,6% reduction in piston surface area. Furthermore, the smaller bore diameter reduces the circumference of the piston rings, directly lowering sliding friction. To minimize friction losses further without the weight penalty of cast-iron liners, the cylinder bore is treated using atmospheric plasma spray technology. This process deposits a micro-thin layer of low-carbon steel and molybdenum composite directly onto the cylinder wall. However, as the specialized equipment required for this advanced coating technique is unavailable within the university's facilities, this manufacturing step must be outsourced to an external company. As in Variant 2, the valve train is operated by the same electromagnetic solenoids. To maximize mechanical efficiency, the design prioritizes the minimization of oscillating mass. The reduced peak forces on the connecting rod resulting from the smaller piston area also contribute to this goal, reducing structural stress. Reducing component weight significantly lowers the energy required for acceleration, which is critical for the intermittent start-stop driving strategy where the engine frequently transitions between operating speeds. The primary advantages of this concept include the potential to achieve the highest mechanical efficiency and the lowest overall weight through the optimization of individual components. However, this approach presents significant challenges, including the highest level of design and manufacturing complexity, substantial development and production costs, and a higher risk of failure associated with unverified components, necessitating extensive prototype testing and tuning. [4,5]

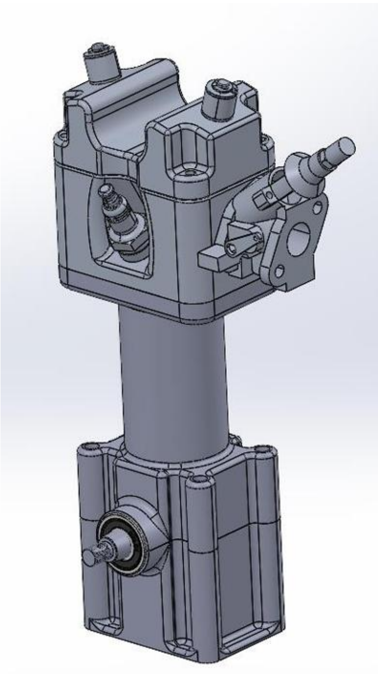

Figure 11 New engine concept

Comparison of the designed variants and manufacturing aspects

Each of the presented variants offers a different approach to solving the problem of engine design for SEM.

- Variant 1 (Modified GX35 without fins) offers a good compromise between using proven technology and the potential for better thermal properties.
- Variant 2 (Simplified geometry GX35) serves as a realistic experimental platform for optimizing valve timing strategies in laboratory conditions, paving the way for the bespoke design of Variant 3.

- Variant 3 (New concept) represents the most ambitious approach with the highest potential for achieving very high efficiency and low weight, but at the cost of the highest complexity, cost, and risk.

IV. CONCLUSION

Based on the comparison of the designed concepts, Variant 3 was chosen as the most promising direction in the context of the competition, that allows for a fully bespoke design solution. While Variant 2 theoretically allows with its new head for advanced cycle approach, it remains constrained by the stock engine's oversquare geometry. This configuration suffers from a large surface-to-volume ratio, which becomes particularly detrimental at low-to-medium engine speeds where the prolonged residence time of working gases leads to excessive heat loss. However, the practical feasibility of the other two designs relies heavily on the energy balance of the valve actuation system. As the analysis of commercial components demonstrated, standard solenoids lack the required force-to-power ratio. Therefore, the currently proposed electromagnetic system is intended primarily as a research tool, and the implementation of last two variants includes designing a new single overhead cam head. For the rapid implementation for the next season, we chose first variant. The successful deployment of Variant 3 in competition is thus conditional on the future development of proprietary high-efficiency actuators that can minimize electrical consumption to a level where it is offset by mechanical friction savings continuing with simulation and testing new components.

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