Investigation of Performance Scaling in Small Internal Combustion Engines

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Power Output Follows Power Law

Why deviation at small scales?

Manufacturer's Data

- OS61
- OS46
- AP Yellowjacket
- AP Hornet
- AP Wasp
- Norvell BigMig
- Cox BabeBee
- Cox Tee Dee
- PAW 0.15
- PAW 0.061

Engine Mass (kg)

Power (W)
Simple Scaling Explanation

\[ q_{\text{loss}} \sim N u l (T_f - T_w) \]

\[ Nu = 3.7 \]

**Power (W)**

- **Fuel power**
- **Heat loss**
Simple Scaling Explanation

\[ q_{\text{loss}} \approx N u l (T_r - T_w) \]

\[ N u = 3.7 \]

![Diagram showing power and power density scaling](image)
Interest/Motivation

- **Size limits of power systems**
  - How small can *practical* power systems be built?
  - What are the limiting factors?
    - Technology
    - Physics

- **Capitalize on existing technology**
  - Applications
    - UAVs
    - Micro-rockets
  - Understand what we can do *today*
Approach

- Detailed performance measurements for four engines of different sizes
  - Torque
  - Speed
  - Fuel flow rate
  - Air flow rate
  - Cylinder head T
  - Exhaust gas T

Power
Efficiency
F/A
Thermal losses
Frictional losses
Focus: BMEP

\[ BMEP = \frac{P}{VN} \]

\[ P = \eta_m \eta_{th} \eta_{ch} \eta_{vol} \rho_{air} VN (\frac{F}{A}) Q_R \]

\[ \eta_m = \frac{P_{fuel} - Q_{env} - P_{mech}}{P_{fuel} - Q_{env}} \]

\[ \eta_{th} = \frac{P_{fuel} - Q_{env}}{P_{fuel}} \]

\[ \eta_{vol} = \frac{Q_{air}}{VN} \]

\[ \eta_{ch} = \frac{\dot{m}_{fuel burned}}{\dot{m}_{fuel}} \]
BMEP also follows power law scaling

\[ y = 659740x^{0.0913} \]

\[ R^2 = 0.5477 \]
Better scaling: Normalized Power vs. Piston Area (Heywood 2000)

Normalized power = BMEP/2

\[ y = 24.842x^{0.0273} \]

\[ R^2 = 0.9903 \]
Dynamometer

- Fuel tank
- Fuel pressure sensor
- Fuel flow meter
- Cylinder Head T
- Muffler
- Exhaust T
- Air flow meter
- Plenum
- Absorber
- Speed Sensor
- Load Cell
Dynamometer

- Fuel Tank
- Cyl. Head T
- Throttle Servo
- Cooling Duct
- Scale
- Exhaust T
- Engine
- Speed Sensor
- Absorber
- Cradle
- Moment Arm
- Load Cell
Data Processing

- Power corrected to STP (ASME standard PTC 19.1)
- Heat loss computed using cylinder head T measurements and Nu correlations from Bubert et. al. 2006
- Frictional losses determined by motoring the engine while measuring torque and speed.
- Chemical efficiency inferred from measurements of output power, F/A, and the other efficiencies.
- Most challenging measurement: Fuel flow
Typical Results (AP ‘Yellowjacket’)
Efficiency Scaling at Peak BMEP

- Efficiencies decrease as size reduce.
- Significant variability between designs.

Graph showing displacement (m³) vs. efficiency (%) with uncertainty bars for different efficiencies and BMEP (Pa).
Efficiency Scaling at Constant F/A

- Decreasing size decreases efficiencies
- Significant variability between designs
Estimation of Minimum Size

Piston engines $A < 8 \text{ mm}^2$ (d < 3.2 mm) not possible
Conclusions

- Identified scaling laws for small engine performance
  - Best correlation between BMEP/2 and total piston area.
- Identified minimum length scale: $\sim 3 \text{ mm}$
- Minimum size/BMEP set by losses
  - As reduce size, losses become proportionally more important
- Best ways to improve performance:
  - Increase volumetric efficiency
  - Implement mixture control
  - Keep characteristic length $> \sim 10 \text{ mm}$
Future Work

• Improve fuel mass flow rate measurement
  – Biggest limitation at this point
• Improve heat loss and friction models
• Test more and smaller engines
• Develop model for chemical reaction
Acknowledgements

We would like to thank the Army Research Office and Dr. Tom Doligalski for supporting this work.
# Fuel

<table>
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<tr>
<th>Component</th>
<th>$\chi$</th>
<th>$\rho$</th>
<th>$Q_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_3$COH</td>
<td>0.7</td>
<td>0.79</td>
<td>22.6</td>
</tr>
<tr>
<td>CH$_3$NO$_2$</td>
<td>0.1</td>
<td>1.11</td>
<td>11.6</td>
</tr>
<tr>
<td>Castor Oil</td>
<td>0.2</td>
<td>0.96</td>
<td>44.0</td>
</tr>
<tr>
<td>Mixture</td>
<td>1.0</td>
<td>0.86</td>
<td>26.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>g/cm$^3$</th>
<th>kJ/g</th>
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<tbody>
<tr>
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Scaling Analysis

\[ \eta = \frac{q_{\text{fuel}} - q_{\text{loss}}}{q_{\text{fuel}}} \]

\[ q_{\text{loss}} \sim \text{Nu} \cdot I \cdot (T_f - T_w) \]

- Power Density (W/m\(^3\))
- Efficiency (%)
- \( l \) (m)
- \( S_L \)

Graph showing the relationship between power density and \( l \).
Fixed-Wing MAV

![Graph showing conversion efficiency and storage efficiency for different energy sources.](image)

**Baseline fixed-wing MAV:**
- \( X_f = 0.1 \)
- \( \eta_p = 0.8 \)
- \( L/D = 2 \)
- Endurance: 0.1 min

**Equation for endurance:**
\[
\tau = \left( \frac{\eta_{pwr}}{g} \right) \left( \eta_{prop} \frac{L}{D} \right) \ln \left( 1 + \frac{m_f}{m_v} \right)
\]
Hovering MAV

**Batteries:**
- Ni-Cd
- Ni-MH
- Li-ion
- Adv. LPB
- DMFC

95% efficient

**Fuel Cell:**
- 85% efficient

**HC Fuels:**
- Fuel Oil, AVgas
- C₃H₈
- C₄H₁₀
- H₂

**Baseline Vehicle Params:**
- Rotor Efficiency = 70%
- Mass = 100g
- Rotor dia. = 10 cm
- Mission = 30 min

Baseline Vehicle Parameters:
- Rotor Efficiency = 70%
- Mass = 100g
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**Equation:**

\[ \tau = \left( \frac{\eta_{pwr} Q_R}{g} \right) \left( \eta_{prop} \sqrt{\frac{\rho_{air}}{L_{disc}}} \right) \left( \frac{m_f}{m_v} \right) \]
Advantage of HC Fuels

- Energy density of HC fuels much higher than electrochemical sources
- Efficiency is the key to exploiting this advantage
  - Simplified by the fact that relatively low conversion efficiency is needed to outperform batteries.
- Efficiency is also the problem
  - As engines become smaller, they become less efficient.
- Challenge:
  - Develop small, highly efficient HC-fueled engines for MAVs
Examples of MAVs

Small flying vehicles:
- Mass < 100 g
- Flight endurance > 60 min
- Applications:
  - Surveillance
  - Chemical Detection
Existing MAV Performance

- Hoverfly [180g/5-10min]
- LuMAV [440g/5-10min]
- Microbat [10g/5 min]
- MicCOR [100g/2.75 min]
- Microcraft DAV [1500g]
- MicroSTAR [110g/25min]
- Objective [100g/60min]
- Black Widow [80g/22min]

Endurance (min) vs Weight (g) graph

Courtesy: Prof. Darryl Pines
Linear trend consistent with findings of McMahon and Bonner
Power Density

Mass (kg) vs. Power Density

- W/l
- W/kg
Power Density (Mass < 1 Kg)

- Large scatter in data
- Power density no longer increases with decreasing size
- Could efficiency be decreasing with size?
Efficiency (Mass < 1 Kg)

- Large scatter in efficiency estimates.
- How fast should efficiency decrease with size?
- How reliable is the data used to make the estimates?