Scaling Laws for Free Piston Engines: Benefits and Challenges of Miniaturization

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Small scale internal combustion engines (less than 10 centimeter in linear dimension) are being designed for powering next generation miniature robots, micro unmanned aerial vehicles (UAVs), and exoskeleton systems. This work presents scaling laws for free-piston engines (FPEs), answering the question: how the physical (engine size) and operating (engine load, combustion) parameters affect the FPE performance? FPEs are internal combustion engines known for their simple architecture, higher thermal efficiency, and higher power output. This work specifically focuses on identifying the benefits and challenges in miniaturizing FPEs. For this, first a simple mathematical model of the FPE is derived by employing first principles such as Newton's second law of motion, conservation of mass, conservation of energy, conservation of momentum, and ideal gas law. Next, nondimensional parameters that capture the contributions of the physical and operating parameters are identified. Then, the effect of the nondimensional parameters on the FPE performance and behavior are studied. Our scaling analysis shows that for an efficient FPE operation, we need to: (1) reduce the piston-cylinder gap to mitigate leakage losses; (2) use a membrane architecture instead of the sliding-piston architecture to reduce friction and leakage losses; and (3) operate the FPE at a very higher frequencies to reduce heat loss.