TECH FRONTIERS

Development of combustion-based micro thermoelectric power generators

Researchers in IIT Bombay, having developed possibly the first microcombustion-based portable power system, are working on optimising the system's efficiency

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OVER the past few decades, rapid progress has been observed in the development of microelectromechanical systems (MEMS) due to the outstanding contributions made in the field of microelectronics, biomechanics, etc. by researchers world over.[1] The majority of the MEMS devices require a reliable and lightweight power source to operate in various research domains for longer service times. Due to recent manufacturing breakthroughs, many avenues for newer innovations in the field of microcombustion have opened up, as it can act as a suitable heat source for various combustion-based power sources.[2] The high specific energy contained in hydrocarbon fuels is 20-50 times higher than the electrochemical batteries. This aspect has motivated researchers to explore the design and development of small-sized combustors to maximise the performance of various small-scale systems.

Figure1 shows the importance of hydrocarbon-powered energy sources compared to conventional electrochemical batteries. As discussed before, the key issues of conventional electrochemical batteries such as burdensome weight, low operational life, and high unit cost necessitate the development of high power density, hydrocarbon fuelled power sources.[3] [3]. The rechargeable batteries are yet to demonstrate specific energy densities greater than 1.2 MJ/kg and a combustion-based power source with an efficiency of ~3 percent can compete with rechargeable batteries. The fact is that the fuel can be easily replaced as well to make it more viable than the rechargeable electrochemical batteries. Certain applications require a direct supply of mechanical power (locomotives, rovers, etc) and/or heat (heaters, etc) and microcombustors can provide this heat directly, without the application of a heating element.

The field of microcombustion has also seen significant growth due to the commercialisation of micro-manufacturing techniques, which enabled accurate and precise fabrication of microdevices on a large scale for low costs. Microcombustors are expected to have lower efficiencies than their macro counterparts due to the high surface-area-to-volume ratio, the concentration of unburnt hydrocarbons, CO, CO2, and other exhaust gases (products of incomplete combustion) is estimated to be slightly higher.[4] In addition to this, the flame stabilisation in microcombustors are also difficult due to the large heat loss to heat generation ratio. However, researchers came up with different flow and heat recirculation techniques to overcome this issue.[5]

Micro gas turbine, thermoelectric generators (TEG) and thermophotovoltaic cell (TPV) are the commonly used techniques to extract electricity from the heat of combustion.[6] A number of turbines/engines have been developed albeit with low conversion efficiencies.[7] Additionally, the moving parts lead to severe leakage and lubrication problems at very small scales. This results in a drop in the compression ratio and increased frictional losses from rotary systems. The direct conversion of heat energy to electric energy gives TEGs and TPV based systems a distinct advantage over microturbines. In addition to the operational advantages of TPV and TEGs, the maintenance cost and the availability of components are also lower compared to the micro gas-turbines.

We have been working on the combustion-driven portable power generation systems for the past seven years. We are essentially focusing on the micropower generation systems, which can be used as alternative power source for the portable electronic devices, such as notebook computers, mobile phones, video camera etc. Working principles are thoroughly explored by this time and we are successful in harvesting a power of ~5W from a system with a comparatively higher conversion efficiency of 5 percent, which is one of the highest in the existing devices with a power density of 0.14mW/mm3. The system compactness and the output power with high conversion efficiency shows the possibility of its application in various portable scale power generators for remote, standalone, military and aerospace applications. The power density (mW/mm3) of this novel concept based micropower generator is ~50 percent higher than the existing similar standalone micropower generation systems.

Different efficient prototypes of a combustion-based thermoelectricmicro power generator with significant improvements in power density and conversion efficiency have been developed in the present study and as shown in **Figure2**.[8-11] The prototypes consist of thermoelectric generators mounted on both sides of a high performance microcombustor configuration along with cooling jackets. The initial study focused on the development of a power generator using a 'single combustor,' which consists of three backward steps, and a rectangu-

Figure1: Engineering export trends (y-o-y), March-May 2020

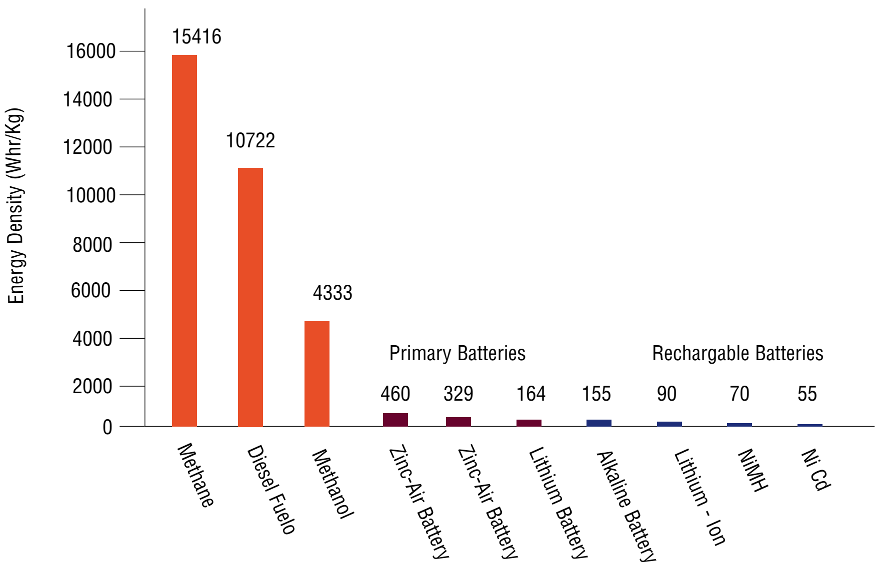
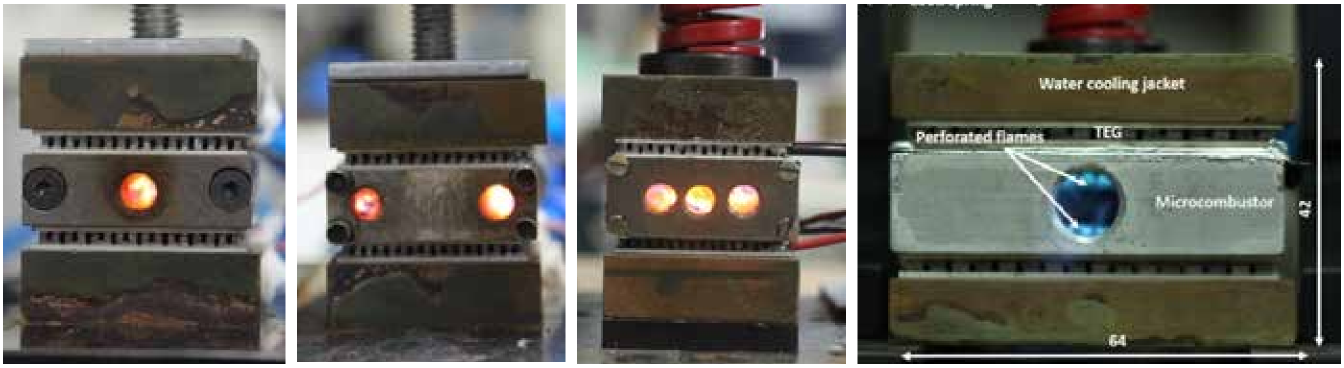


Figure2: Prototypes of micro power generators developed



lar heating medium containing heat-recirculation holes. A detailed parametric study is carried out by varying the mixture inlet velocity, equivalence ratio, and coolant flow rate to obtain the optimum operating conditions for maximum power generation. A power output of 3.89W with an overall conversion efficiency of 4.03 percent is achieved at an equivalence ratio of 0.9 and a mixture velocity of 10m/s. The study is then extended to a new dual microcombustor (two microcombustors in same configuration) to further enhance the flame stability and thermal performance of the system. This enhancement is attributed to the improved flame-to-wall interactions.

A maximum power output of 4.5W with a conversion efficiency of 4.66 percent was achieved using this configuration. The role of different passive and active cooling methods on power generation was also investigated. Air-cooled power generators yielded 2.4W electric power with 2.5 percent overall conversion efficiency, which is ~50 percent less than that of water-cooled systems. In a triple microcombustor configuration, a novel technique to extract maximum heat from the hot combustion products for thermoelectric power generation is implemented. The thermoelectric modules are mounted appropriately to facilitate a direct contact of the thermoelectric module surface with the hot combustion products. A significant improvement in heat transfer rate from the hot combustion products to the thermoelectric modules (~16 times) is achieved, resulting in an electric power output of 4.9W with overall conversion efficiency of 5.09 percent, at a mixture velocity of 10m/s and a mixture equivalence ratio of 0.9. This results in an improvement of ~10–20 percent in the overall conversion efficiency, as compared to previously reported systems.

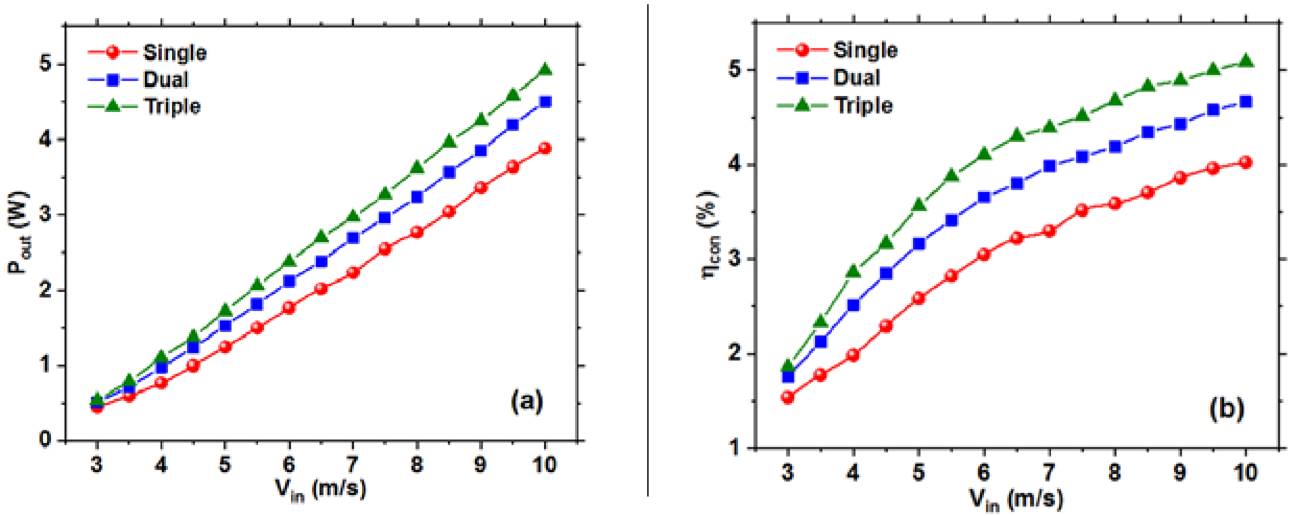
Figure3a and **b** show the variation of the output power and conversion efficiency of the three combustor configurations with the inlet mixture velocity. The output power and conversion efficiency show an almost linear trend with the mixture velocity, with the most optimum results reported in case of the triple combustor configuration. An output power of 3.89W, 4.5W, and 4.9W is achieved at mixture velocity of 10m/s at a fixed equivalence ratio for the single, dual, and triple combustor configurations respectively. The enhanced performance for the triple combustor configuration can be attributed to two factors. First, the presence of additional combustion zones improves the preheating of the unburnt fuel-air mixture. Second, the triple combustor configuration allows the exhaust gases to flow through a rectangular channel at the periphery of the combustor, thereby facilitating direct contact between the exhaust gases and hot side of the TEG, leading to an increased power output. As a result, a conversion efficiency of 5.09 percent is achieved for the triple combustor configuration, which is almost a 10 percent improvement over the reported efficiency of 4.66 percent for the dual combustor configuration.

The power delivering flexibility of the proposed prototype for operating under different output conditions is shown in **Figure4**. The dotted circle in the figure shows the operating point of the present system and the corresponding output voltages of different AA batteries. The details of the operating conditions of TEG to match the different AA battery performances are tabulated in **Table1**. It can be identified from Figure4 and Table1 that to achieve the output voltage of NiMH, Alkaline, NiZn, and Li-ion, the present device requires heat inputs of approximately 33.8W, 38.6W, 43.5W, and 96.6W respectively.

Figure5 demonstrates the variation of the conversion efficiency of the system with its power density for different TEG and TPV studies. The triple combustor configuration has reported the highest conversion efficiency of 5.09 percent with a power density of $0.14 mW/mm^3$, which is significantly higher than its counterpart studies. It is noteworthy that none of the other studies have managed to produce a conversion efficiency >5 percent while operating at a power density $>0.14 mW/mm^3$.

Furthermore a scaled system with

Figure3: Variation of (a) output power and (b) conversion efficiency with mixture velocity for different combustor configurations



higher power output has been prototyped employing a new perforated plate combustor configuration shown in **Figure6a**. The design of this combustor is similar to the household cooking burners. It has been shown to achieve a high heat-flux with superior temperature uniformity on the combustor surface. An improved thermal performance is attained due to the simultaneous flame-flame interaction and flame impingement on combustor walls. This system has been shown to achieve a power output of 21.2W with 3.09 percent conversion efficiency. The electric power output of the system is used to power four 6W LED bulbs, thereby demonstrating its practical and commercial viability as shown in Figure6a.

To commercialise the development of combustion-based TEGs, a standalone

Figure4: Performance comparison of the present system with the AA batteries

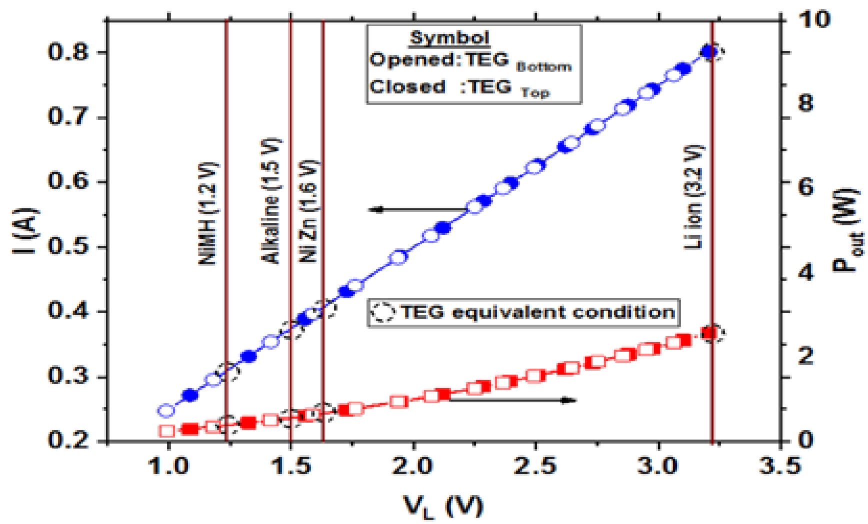


Table1: Output comparison of present micropower generator with AA batteries										
AA battery		**Present micropower generator characterisation**								
		TEGTop			**TEGBottom**			**RL (Ω)**	**mf(g/min)**	**ηcon (%)**
	VL (V)	**VL (V)**	**I (mA)**	**Pout (W)**	**VL (V)**	**I (mA)**	**Pout (W)**			
NiMH	1.2	1.33	330	0.44	1.18	300	0.35	4	0.045	2.33
Alkaline	1.5	1.55	389	0.61	1.42	350	0.5	4	0.051	2.86
NiZn	1.6	1.72	432	0.75=	1.59	400	0.63	4	0.058	3.16
Li ion	3.2	3.21	802	2.57	3.06	770	2.35	4	0.13	5.09

portable power generator is developed, as shown in **Figure6b**. The overall system occupies a volume of 120 × 95 × 75 mm3 with a weight of 400g. Acrylic is used as the material of construction. Due to the bulky nature of a water-cooled system, aluminium fins are used for cooling along with a CPU fan (perpendicular to the direction of the fin), along with an auxiliary unit to deliver the premixed fuel-air mixture. Although the system could still be further optimised, this system may be the first microcombustion-based portable power system developed, according to the authors' knowledge.

Figure5: Performance comparison of micro power generators with other similar micro power generators

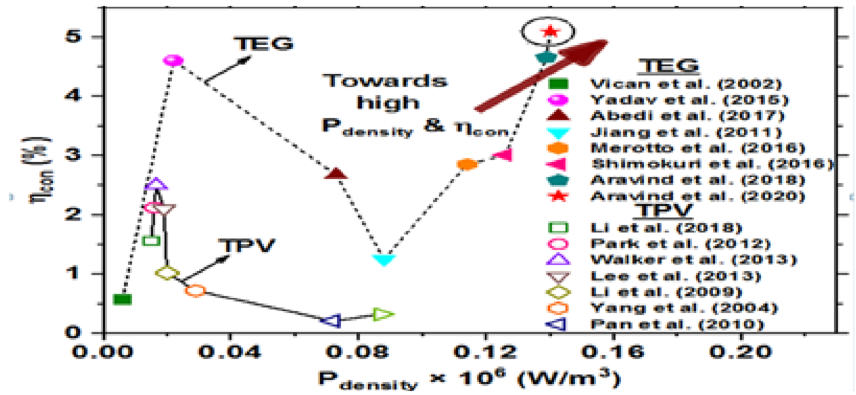
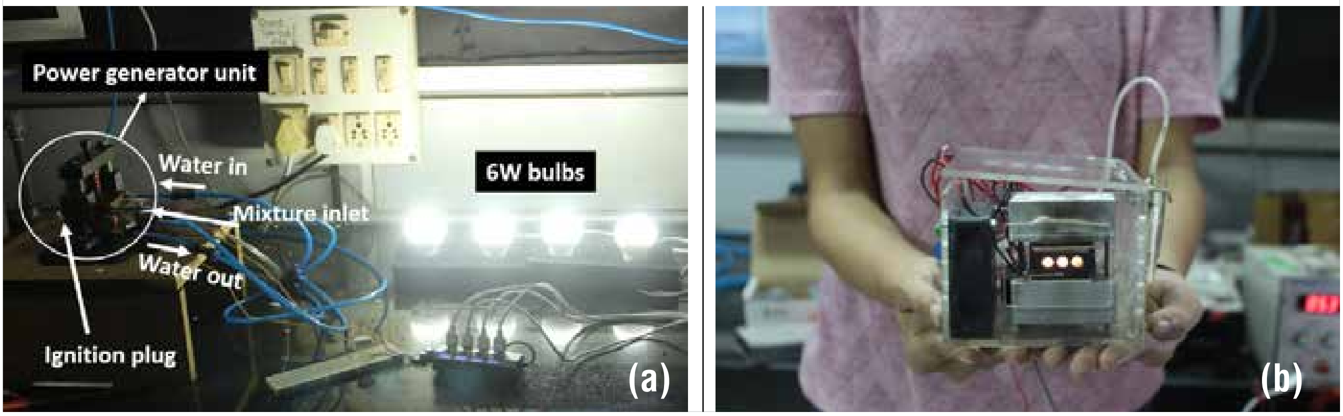


Figure6: (a) Prototype of high wattage system; and (b) standalone micro power generator developed



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