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Supplementary Materials

Self-Powered and Robust Marine Exhaust Gas Flow Sensor Based on Bearing Type Triboelectric Nanogenerator

Description S1: Start-up speed requirement of the B-TENG

The power of the main engine varies in a wide range due to the change of navigation condition of the ship. Generally, the exhaust gas flow measuring should cover that under 25%, 50%, 75% and 100% of the engine power for E3 working cycle. Taking an actual main engine as an example, the main working parameters of which are shown in Table S1.

Table S1. Main working parameters of an actual main engine on a ship.

Items	Parameters
Type	Low speed two stroke diesel engine
Number of Cylinders	6
100% Power (Contracted Maximum Continuous Power)	4440 kW
Specific Fuel Oil Consumption	178 g/kWh + 3%
Dimension of Exhaust Gas Pipe	Φ 801.3 mm (Outer Diameter) × 6 mm (Thickness of Pipe Wall)

It needs about 14 kg of air to burn 1 kg of HFO completely in theory. According to the actual working condition of the diesel engine, complete burning 1 kg of HFO need more air than that in theory. The ratio of the actual air for burning 1 kg of HFO to that in theory is called the excessive air coefficient, and this coefficient is mainly in the range of 2-3 for different diesel engines. Consequently, the exhaust gas flow velocity can be estimated by Equation S1 according to principle of mass conservation.

$$V_g = \frac{Q}{S} = \frac{P \cdot g \cdot (1+\alpha \cdot 14) / \rho \cdot 3600}{\pi r^2}, \tag{S1}$$

where, V_g is the exhaust gas velocity, Q is the exhaust flow, S is the cross-section of the exhaust gas pipe, P is the working power of the main engine, g is the specific fuel oil consumption (SFOC), α is the excessive air coefficient, ρ is the exhaust gas density, r is the radius of the exhaust gas pipe.

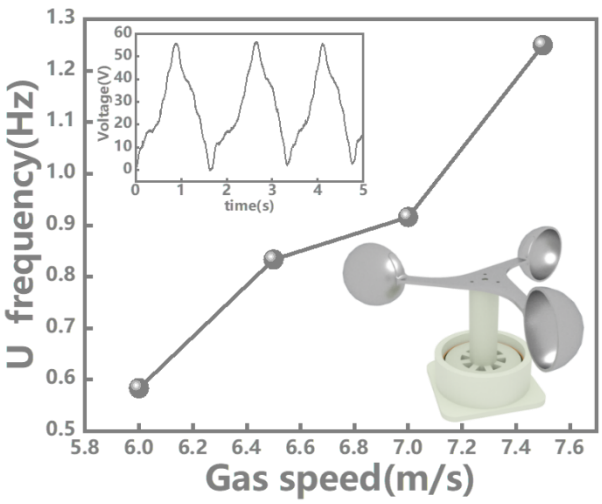

Figure S1. The start-up speed of the original B-TENG.

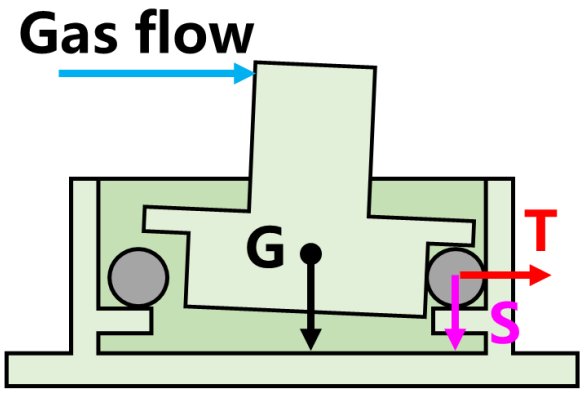

Figure S2. The acting force analysis of the original B-TENG.

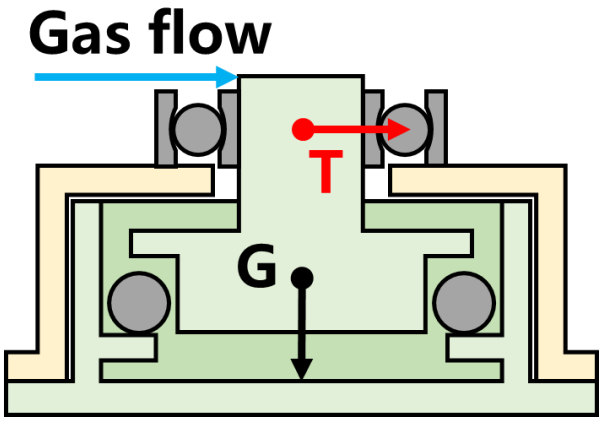

Figure S3. The acting force analysis of the final B-TENG.

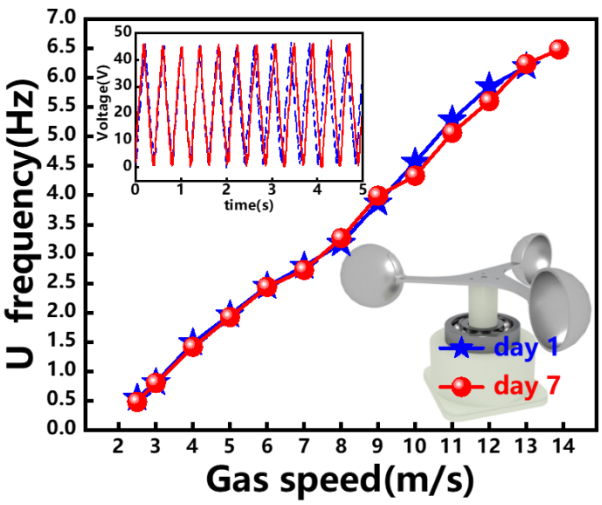

Figure S4. The start-up speed of the final B-TENG.

The start-up speed of the original B-TENG is about 6 m/s, which is higher than the gas flow speed under 25% of the engine power, and doesn't meet the requirement. That is because the gas flow force acting on the rotating scoop will result in the lateral force acting on the cactus stent. As illustrated in Figure S2, this lateral force causes the center of the cactus stent away from the center of the stator. It leads to increasing of the thrust (T) and stress (S) force on the ball, and then increases the friction between the rotor and the stator. To lower the minimum start-up speed, this lateral force should be balanced, so the structure of the B-TENG has been optimized to accommodate the exhaust gas flow range in

this work. As shown in Figure S3, the lateral force is balanced by the enclosed lubricated bearing, which undertakes the thrust (T) and ensure the center line of rotor and stator always coincide as well. Figure S4 exhibits that the B-TENG can start and rotate smoothly at gas speed of 2.5 m/s. It meets the requirement of the main engine minimum gas speed working at 25% power. Furthermore, as exhibited in Figure S4, the relations between the gas speed and the FFT result keeps in well correspondence even after 7 days. The voltage signals on day 1 and day 7 are depicted in the inset of Figure S4, and show a good consistency.

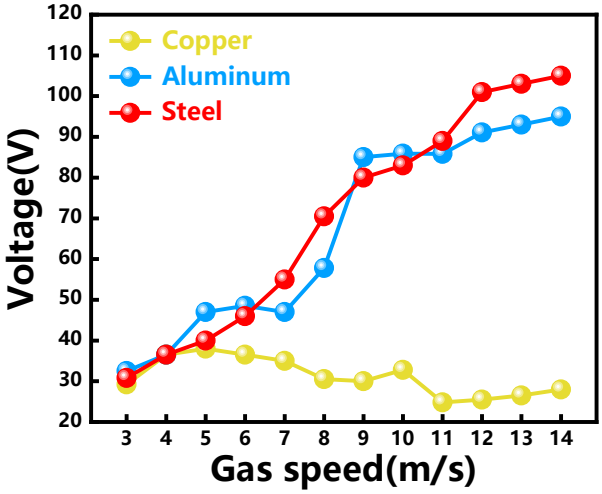

Figure S5. The output performance of the B-TENG with copper, aluminum and steel balls under different gas speed.

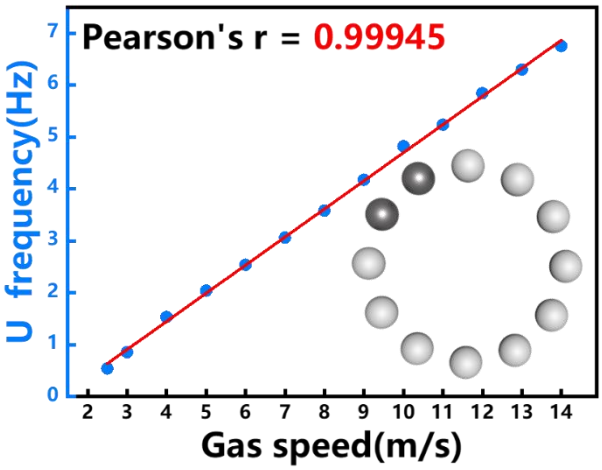

Figure S6. The FFT results of the output voltage signal of the B-TENG with 2 steel balls under different gas speed.

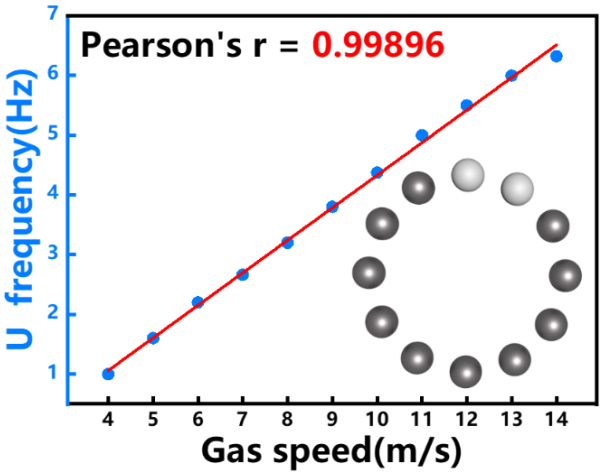

Figure S7. The FFT results of the output voltage signal of the B-TENG with 10 steel balls under different gas speed.

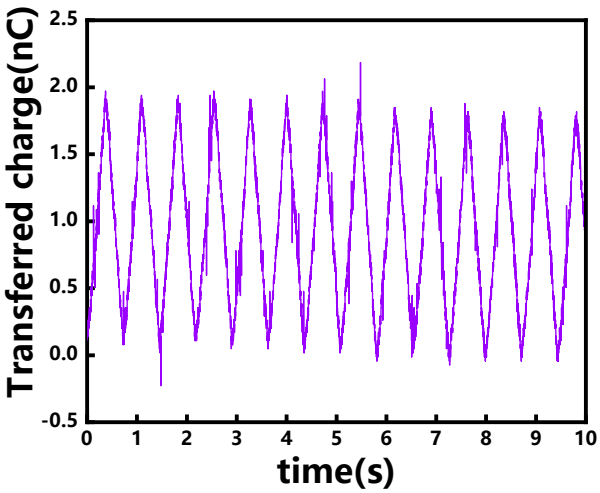

Figure S8. The transferred charge under the PM concentration test.

Video S1: Minimum start-up speed test of the B-TENG in Version 4.0;
Video S2: Effects of PM on the output performance of the B-TENG;
Video S3: Heating process of the B-TENG in the heating box at 180 °C for 10 minutes;
Video S4: Demonstration of the B-TENG as the gas flow sensor.