OPTIMIZATION THEORY FOR BALLISTIC ENERGY CONVERSION
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ABSTRACT
The growing demand of renewable energy stimulates the exploration of new materials and methods for clean energy. We recently demonstrated a high efficiency and power density energy conversion mechanism by using jetted charged microdroplets, termed as ballistic energy conversion. Hereby, we model and experimentally characterize the physical properties of the ballistic energy conversion system.

KEYWORDS: Ballistic energy conversion, microdroplets, theoretical modeling

INTRODUCTION
We recently obtained nearly 50% efficiency by decelerating high speed charged droplets with a metal target, as we termed “ballistic energy conversion”, by taking advantage of the high surface to bulk ratio in a form of the air/water interface\citep{1,2,3}. Moreover, the mechanism strongly differs from the previously electrokinetic energy conversion methods, thus the optimal performance and driving conditions of the system need to be assessed \citep{4}. In this paper, we present a theoretical model based on an optical characterization of the conversion system and predict the most important performance characteristics when operated as an energy converter.

MODELS AND EXPERIMENTAL SETUP
- Models
As stated above, we separate the ballistic energy conversion into two stages: accelerating stage, water was pressing out of the pore and forming high speed charged droplets with efficiency \( \text{eff}_{\text{kin}} \); decelerating stage, the droplets were decelerated by joint action of generated electrical fields and air friction with efficiency \( \text{eff}_{\text{el}} \). To estimate the upper limit of ballistic energy conversion efficiencies of ballistic energy conversion, we could deduct the magnitude of the modeled energy loss during these two consecutive energy conversion processes. The system efficiency can be expressed by \( \text{eff}_{\text{sys}} = \text{eff}_{\text{kin}} \cdot \text{eff}_{\text{el}} \).
- Experimental Setup

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a). Mechanical energy losses in the model. (b) Setup for optical velocity measurements. (c). Sample picture by double illumination of droplets from the droplet stream from a 30\,\mu m pore. Images are taken with 10\,\times\ objective and displayed on 4.65\,\mu m pixels. Scale bar indicates 25\,\mu m.}
\end{figure}
We use an optical system to characterize the droplet speed (Fig 1), to quantify the energy losses in the accelerating and decelerating stages. The droplet information was calculated by double-illumination images which can illustrate the moving distances within a few nanoseconds, provided by two Laser pulses. Finally, by extracting the information of the droplet speed as a function of several physical quantities, eg. the travelling distance, electrical field strength and applied pressure, we could test our physical models by such optical characterization.

RESULTS AND DISCUSSION

Our results show that the efficiency in the acceleration stage directly relates to the jet radius and Weber number. Working with a high Weber number and a large jet size seem to help increasing the system efficiency (Fig 1a). However, the oversized jet and over high We won’t induce an efficient energy convertor considering the effect on the other performance factors like power density and the generated target voltage (Fig 1c). We adopted the area of $(4 \times a)^2$ as the energy generation cell, and the power density decreases with the jet radius (lower surface to bulk ratio), but increases with $We$.

![Figure 2](image)

Figure 2. (a). The upper limit at high We of eff_kin, eff_el and eff_sys (system efficiency) as a function of jet radius $a$. The system efficiency increases rapidly due to a decreasing energy loss by air friction, and is dominated by viscous losses when $a>25\mu m$. Both the efficiencies with (solid lines) and without (dashed lines) air wake (surrounding air flow induced by moving droplets) were calculated showing efficiencies without wake were overall smaller than with air wake due to lower air friction energy losses. (b). The power density decreases with $a$ at various Weber numbers. (c). The generated voltage increases with the jet radius at different Weber numbers.

CONCLUSION

From the analysis we predict the key performance factors of conversion efficiency, power density and generated target voltage. Our results show that efficiency increases with jet radius while power density and working voltage decrease, with an optimal radius around 25$\mu m$. The results show that by using maximally charged droplets (up to the Rayleigh limit), a 25$\mu m$ microjet/pore and a proper initial velocity, the system efficiency can be over 90%, at a generated voltage below 1 kV and a power density of at least 100W/m$^2$. The combination of high efficiency, giant power density, simplicity and compactness makes the ballistic energy conversion generator a promising device for green energy conversion.

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