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Microscopic energy conversion process in the ion drift region of electrohydrodynamic flow

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We theoretically investigated the momentum transfer and energy conversion process of ion-neutral and ensuing neutral-neutral collisions in the ion drift region of electrohydrodynamic flow. Our results are presented in explicit equations with physical interpretations of the phenomena. The unit conversion process was estimated to sustain for 1.0 nano-second in a very tiny 0.5-μm-sized volume in the air. Also, the continuum-based equation formulations are presented according to the microscopic energy conversion phenomena. Numerical simulations reflecting those formulations are performed to verify the theoretical results and experimentally supported by an air corona discharge. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4729443]

In a point-to-plane corona discharge, a small ionization region with high electric field is formed around the point, where chemical energy conversion process (ionization, ozone formation, etc.) occurs.1,2 On the other hand, in the unipolar ion drift region connected in series with the ionization region between the point and the plate,1,2 ions acquire momentum and energy from the applied electric field and transfer them to the surrounding neutral molecules through ion-neutral collisions, consequently, inducing an EHD (electrohydrodynamic) flow.3–8 This molecular collision process in the ion drift region generates a thrust, and a reactive air flow called an ionic wind, that can be applied for flow control4,5 and electric propulsion.6,8–10 Most previous studies for this process agree on the fundamental phenomenon: ion-neutral collision. However, they show much disagreement about the explicit equations representing the electric-to-kinetic energy conversion efficiency. In the 1960s,3,8,11 and in 1985,2 Bondar and Bastien12 conceptually formulated ηK using only fluidic parameters as ηK = 1/(1 + Ua/Ua), where Ua is the ion drift velocity and Ua is the neutral fluid velocity. Other studies have presented ηK = Ua/(2Ua)13 and ηK = √ε/ε,14 where ε is the air permittivity and μ is the ion mobility. These disagreements are thought to have occurred because all these equations were formulated based on continuum mechanics with different assumptions for the macroscopic conditions without a clear understanding of ion-neutral collision. In this paper, we try to understand the molecular energy conversion process in the ion drift region for just one ion-neutral collision and the following neutral-neutral collisions. We derive the theoretical equations representing this microscopic conversion process. Also, we provide physical interpretations for the energy conversion phenomena and continuum-based formulations based on microscopic analysis.

Figure 1 illustrates a schematic microscopic energy conversion process in the EHD flow. The average three-dimensional translational velocity of an ion should be the same as the macroscopic ion velocity Ua + Ua (the ion drift velocity Ua = μE, where E is the applied electric field and Ua is the convective fluid velocity). The ion acquires the average translational momentum f · Δt and the average translational kinetic energy f · Δt between the successive ion-neutral collisions from E, where f is the Coulomb’s force qE (q: ion charge quantity, Δt: mean travel time, Δt: mean travel distance). In this paper, we refer to the translational momentum and the translational kinetic energy as the momentum and the kinetic energy, respectively. Hence, the electrical input energy into an ion can be expressed as follows by using ΔI = (Ua + Ua)Δt relation:

\[ f \cdot \Delta t = \frac{q^2}{\mu} U_a \cdot (U_a + U_a) \Delta t. \]  

This equation implies that the electrical energy supplied to the ion can be decomposed into the kinetic energies caused by Ua and Ua. If we assume the ion-neutral collision is elastic, f · Δt and f · Δt are transferred from the ion to the neutral through each ion-neutral collision (s = 0 in Fig. 1). The neutral molecule moves to the right with the increased momentum f · Δt and the increased kinetic energy f · Δt. Subsequently, it collides with other neutral (s = 1 in Fig. 1). This first neutral-neutral collision following the ion-neutral collision triggers one more neutral to move to the right by transferring some portion of f · Δt and f · Δt (s = 2 in Fig. 1), and subsequently two neutrals trigger 4 molecules to move to the right (s = 3 in Fig. 1), and so on (dissipation zone in Fig. 1). Finally, all the neutrals influenced by the ion-neutral collisions, henceforth denoted as a colony in this paper, will smear out into the overall flow motion Ua (conservation

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zone in Fig. 1). We assume that the ion and the neutrals have the same mass \( m \). The total kinetic energy \( e_k \) of one molecule can be expressed as \( e_k = \frac{1}{2}mU^2 + \frac{3}{2}kT \), where \( U \) is the translational velocity, \( k \) is the Boltzmann constant, and \( T \) is the temperature \( (K) \).\(^{15} \) \( f \cdot \Delta t \) and \( f \cdot \Delta l \) should be conserved through all these collision (non-colony member) events. We can express the momentum and energy conservations for the colony members in the final stage of Fig. 1 as follows:

\[
\begin{align*}
\mathbf{f} \cdot \Delta t + \eta_f m \mathbf{U}_a &= \eta_f m (\mathbf{U}_a + \Delta \mathbf{U}_a), \\
\mathbf{f} \cdot \Delta l + \eta_f \frac{1}{2} m U_a \cdot \mathbf{U}_a + \eta_f \frac{3}{2} kT_a \quad &\text{where } \eta_f \text{ is the number of colony members, } \Delta \mathbf{U}_a \text{ the average velocity increment of the colony members in the final stage, and } T_a \text{ and } T_f \text{ are, respectively, the temperatures before and after becoming colony members.}
\end{align*}
\]

\[
\begin{align*}
\eta_f &= \frac{1}{2} m (\mathbf{U}_a + \Delta \mathbf{U}_a) \cdot (\mathbf{U}_a + \Delta \mathbf{U}_a) + \frac{3}{2} kT_f, \\
&= \eta_f \left( \frac{1}{2} m \mathbf{U}_a \cdot \mathbf{U}_a + \Delta \mathbf{U}_a \cdot \Delta \mathbf{U}_a + \frac{3}{2} kT_f \right), \\
\end{align*}
\]

\[
\Delta E_K = \frac{qI}{\mu} \mathbf{U}_d \cdot \mathbf{U}_d \Delta t. 
\]

Hence, the electrical to kinetic energy conversion efficiency \( \eta_K = \Delta E_K / (f \cdot \Delta l) \) and the electrical to thermal energy conversion efficiency \( \eta_T = \Delta E_T / (f \cdot \Delta l) \) are expressed as the following equations:

\[
\begin{align*}
\eta_K &= \frac{\mathbf{U}_d \cdot \mathbf{U}_a}{\mathbf{U}_d \cdot (\mathbf{U}_d + \mathbf{U}_a)}, \\
\eta_T &= \frac{\mathbf{U}_d \cdot \mathbf{U}_a}{\mathbf{U}_d \cdot (\mathbf{U}_d + \mathbf{U}_a)}. 
\end{align*}
\]

The above two equations become \( \eta_K = U_d/(U_d + U_a) \) and \( \eta_T = U_d/(U_d + U_a) \) when \( \theta = 0^\circ \) (see Fig. 1).

In the above neutral-neutral collisions in the dissipation zone, the thermal velocity \( U_T = \frac{1}{2} m U_T^2 \) is included in the actual three-dimensional motions. Without loss of generality, this complicated state can be transformed into a binary collision system:\(^{16} \) the colony molecule is a projectile with a velocity \( U_p \) \((| \Delta U_a | \leq | U_p | \leq | U_d |) \), and the target is the stationary non-colony molecule. In this collision system, the average energy loss fraction of the projectile is 1/2 per each collision.\(^{16} \) Hence, the first colony neutral (which experienced the ion-neutral collision) exhibits a kinetic energy lower than 1% of the initial value after undergoing 7 consecutive collision stages \((s = 1 \text{ through } s = 7, \text{ Fig. } 1) \). If we take this 1% of the energy level as the criteria for the final stage, the final stage colony is composed of \( 128 (= 27) \) neutrals, and they experience 1 to 7 collisions in the chain collision process. In standard air conditions (mean free path: 0.066 \( \mu \)m, mean thermal velocity: 462.9 m/s at 20°C),\(^{17} \) we can roughly estimate the average process time (the survival time of a colony) as 1.0 nano-second \((0.066 \mu m \times 7/462.9 m/s) \) and the average colony size as \( 0.5 \mu m \) \((0.066 \mu m \times 7) \). Considering that the actual velocity of a
colony neutral \((U_T + U_p)\) is greater than the thermal velocity \(U_T\) of a non-colony neutral, the average process time should be shorter than 1.0 nano-second. In this regard, the microscopic energy conversion process can be said to be an almost instantaneous phenomenon occurring in a very tiny volume. This suggests that we can treat the energy conversion process on a continuum basis.

As a physical interpretation of the above microscopic process, a comparison of the electrical input energy into an ion (Eq. (1)) with the energy conversion results (Eqs. (4) and (5)) suggests that the electric energy input caused by the fluid velocity \(U_a\) is conserved in the flow, while the other portion caused by the ion drift velocity \(U_d\) is dissipated into thermal energy through neutral-neutral collisions. This mechanism can be used for the continuum based energy conversion formulation. Consider a very small volume \(\Delta v\) (which includes at least one colony) drifting in 3-dimensional space with unipolar charge density \(q\) when the electric field is \(E\). The Coulomb’s force exerted on this volume is \(\Delta F = qE\Delta v\) so that the electric power input into this volume is \(qE \cdot (U_d + U_a)\Delta v\) (corresponding to Eq. (1)). The conversion rates (W/m\(^3\)) into the kinetic energy and the thermal energy are \(qE\cdot U_a\Delta v\) (corresponding to Eq. (4)) and \(qE\cdot U_d\Delta v\) (corresponding to Eq. (5)), respectively. However, some portion of \(qE\cdot U_a\Delta v\) should be converted into thermal energy due to the fluid dissipation process,\(^{18}\) which is independent of the above colony process. This quantity can be expressed as \(\varepsilon_T\Delta v\) (\(\varepsilon_T\): fluidic dissipation rate). Therefore, the above 4 equations in order can be expressed as the integral forms in the whole domain: \(\int qE \cdot (U_d + U_a)dv\), \(\int qE \cdot U_a dv\), \(\int qE \cdot U_d dv\), \(\int \varepsilon_T dv\), and overall \(\eta_K\) and \(\eta_T\) are expressed as follows:

\[
\eta_K = \frac{\int (qE \cdot U_a - \varepsilon_T)dv}{\int qE \cdot (U_d + U_a)dv}, \tag{8}
\]

\[
\eta_T = \frac{\int (qE \cdot U_d + \varepsilon_T)dv}{\int qE \cdot (U_d + U_a)dv}. \tag{9}
\]

Under the conditions of constant \(\theta\), \(|U_a| \ll |U_d|\), and negligible \(\varepsilon_T\), Eq. (8) leads to the relation, \(\eta_K \propto \frac{\varepsilon_T}{U_a}\), which was experimentally proven by Kim et al. (Ref. 19).

We performed an experiment to verify the proposed energy conversion process in a wire-to-converging plate corona discharge configuration\(^7\) (Fig. 2(a)) in air, and a numerical simulation reflecting above formulations was performed (Figs. 2(b)–2(f)). The two-dimensional Poisson equation and the charge conservation equations coupled with the continuity and momentum equations were solved using Fluent according to our previous studies (Refs. 10 and 20). In this paper, we additionally solved an energy equation where the thermal energy conversion rate \(qE \cdot U_d + \varepsilon_T\) was used as the energy source distributed in the whole domain. As shown in Fig. 2(b), the tilted collector configuration produces denser electric lines in the right side of the emitter, which indicates a stronger electric field, so that Coulombic body force to the right side with respect to the emitter is higher than the one to the left side (Fig. 2(c)). Consequently, this results in a weak air flow to the right (Fig. 2(d)). Unbalanced body force distribution generates a swirl in the left side of the emitter. The thermal energy conversion rate \(qE \cdot U_d\) (Fig. 2(e)) produced the temperature profiles as shown in Fig. 2(f) due to the air flow directed from the inlet to the outlet.

**FIG. 2.** (a) Schematic cross-section of horizontal experiment set-up. (b)–(f) Simulation results corresponding to (a) for applied voltage = 10 kV, current 0.576 mA, where only the partial upper half domain is shown out of the total calculation domain (symmetrical with respect to the center, width 350 mm, height 100 mm). a: high voltage power supply (ULTRAVOLT, 15A24-N30), b: shunt resistor (100 kΩ, used for current measurement), c: insulator, Rig width (length of emitter and collectors): 200 mm, emitter: diameter 0.04 mm (tungsten wire). Collector (aluminum foil) was attached on the insulator (Styrofoam, 5 mm thickness) surface in order to minimize the heat transfer into the collector. (b) Electric potential lines (red: 150 V, blue: –10 kV), (c) body force in the flow direction (blue: –300 N/m\(^2\), yellowish green: 0 N/m\(^2\), red: 300 N/m\(^2\), blue (negative value) and red (positive value) mean the forces to the left and the right, respectively), (d) path-lines of air flow with velocity (blue: 0 m/s, red: 1.4 m/s), (e) thermal energy conversion rate (blue: 0 W/m\(^3\), red: 200 000 W/m\(^3\)), (f) profiles of temperature rise with respect to the ambient inlet temperature (blue: 0 °C, red: 2.0 °C). The viscous model for the simulation is turbulent (Reynolds stress).
The experimental current 0.589 mA was almost identical to the simulation current 0.576 mA (0.576/0.589 = 0.98) when \( \mu = 2.0 \times 10^{-4} \) m²/V·s.⁵ Considering the simulated current density \( j = q \mu E \) in the discharge space and the current (integral of \( j \) on the collector surface), we can say that simulated \( q \), \( E \) fields are almost the same as the experimental ones. Figure 3(a) reveals decent agreement between the experimental velocity and the simulated velocity both in the inlet and the outlet when the simulated flow is turbulent. Those results agree with the previous experimental conclusion for the same electrode configuration (Tsubone et al.; the flow was always turbulent or limited re-circulating laminar flow, M-shaped outlet velocity profile). The agreement of velocities between the experiment and the simulation re-confirms that simulated \( q \), \( E \) fields are similar to the experimental ones because we used Coulomb’s force \( (\mathbf{F} = q \mathbf{E}) \) as the body force in the momentum equation in order to obtain the \( U_a \) field. Also, the above result suggests that the simulated \( U_a \) field in the discharge volume (a volume enclosed by the inlet, outlet and collectors) would be close to the experimental \( U_a \) field. In this regard, we presumed that the simulated total kinetic energy generation rate 0.00333 W (\( \int q \mathbf{E} \cdot \mathbf{U}_a d\mathbf{V} \)) would be close to the experimental one.

Figure 3(b) reveals good agreement between the experimental outlet temperature profile and the simulated one (turbulent). The macroscopic energy conversion process for the discharge volume can be written as follows for the steady state incompressible flow condition neglecting heat transfer to the collectors:

\[
P_{in} = \int_0^1 \mathbf{F} \cdot (\mathbf{U}_d + \mathbf{U}_a) d\mathbf{V}
\]

\[
= \rho C_p \int_{A_o} U_o (T_o - T_i) dA + \frac{1}{2} \rho \left( \int_{A_o} U_o^3 dA - \int_{A_i} U_i^3 dA \right),
\]

\( (P_{in}: \text{electric input power}, \rho: \text{air density (1.204 kg/m}^3\text{ at 20}^\circ\text{C}), C_p: \text{constant pressure specific heat (1002.8 J/kg·K at 20}^\circ\text{C}), A_o: \text{outlet area, } U_o: \text{outlet velocity, } T_o: \text{outlet temperature, } A_i: \text{inlet area, and } U_i: \text{inlet velocity}) \).

The above process was calculated as \( (P_{in} = 5.76 \text{ W} \Rightarrow 5.72 \text{ W} \Rightarrow 5.62 \text{ W} + 0.00062 \text{ W}) \) for the simulation and \( (P_{in} = 5.85 \text{ W} \Rightarrow 5.79 \text{ W} + 0.00067 \text{ W}) \); we could not measure \( \int \mathbf{F} \cdot (\mathbf{U}_d + \mathbf{U}_a) d\mathbf{V} \) for the experiment. The overwhelming part of the energy goes into gas heating in the corona discharge.⁶ Hence, we think that the similarity between 5.62 W and 5.79 W is essential in supporting the microscopic electric to thermal energy conversion process, even though we did not consider the electric to chemical energy conversion process in our simulation. Also, the agreement of 0.00062 W and 0.00067 W supports the electric to kinetic energy conversion process. Those values are lower than 0.00333 W (\( \int q \mathbf{E} \cdot \mathbf{U}_a d\mathbf{V} \)). We think the balance 0.00266 W (0.00333–0.00067 W) was converted to increase the pressure between the inlet and the outlet, or converted to thermal energy through the fluidic dissipation process. The experimental \( \eta_K \) in the previous studies⁵,¹⁹ was evaluated by the definition: \( \frac{1}{2} \rho \int_{A_h} U_o^3 dA \) over \( P_{in} \), which was calculated as 0.0146% (0.000841 W/5.76 W) in our simulation and as 0.0147% (0.00086 W/5.85 W) in our experiment. These values are quite lower than the previous \( \eta_K \) values of about 1.0% (Refs. 3, 5, and 19) due to the high \( \theta \) (close to 90°) in our case.

In conclusion, we propose a model for the microscopic energy conversion process in the EHD flow. Based on the model, we formulated microscopic-to-macroscopic equations describing this process, which were numerically and experimentally supported. We suppose that our model and approach method will be helpful in the investigations of electrical discharges in the flow field.
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