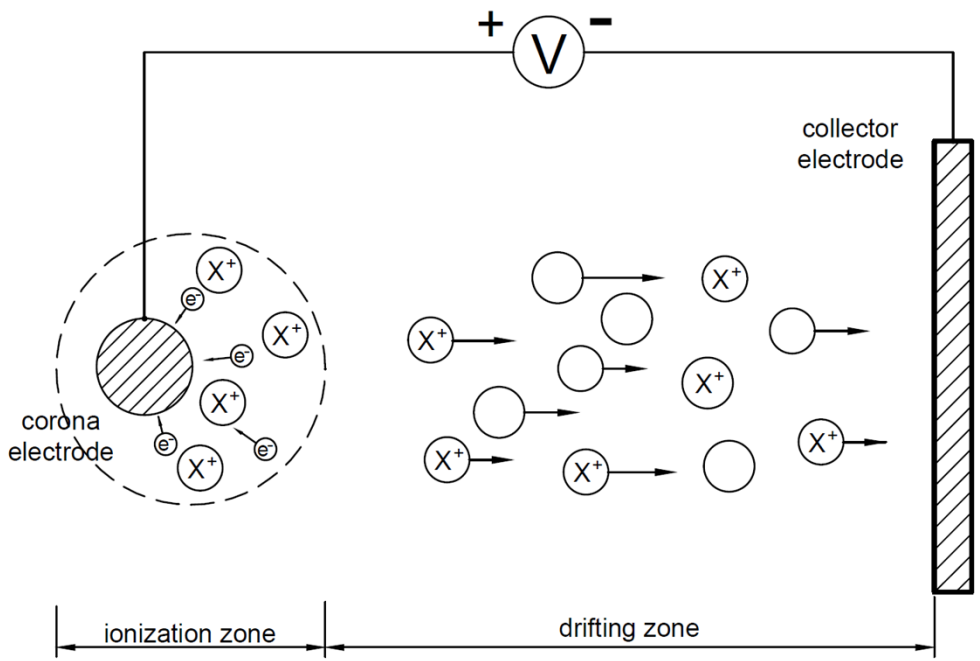
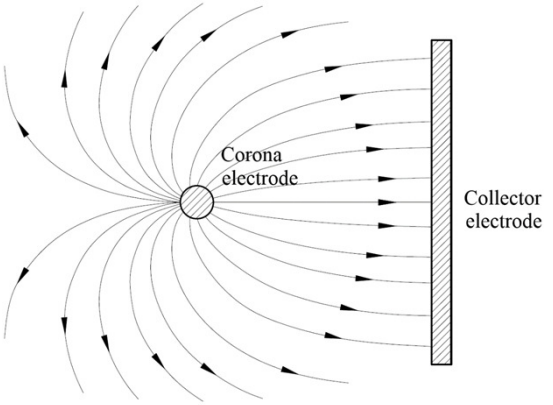
Heat Transfer Enhancement by Corona Discharge

Yeng-Yung Tsui, Yu-Xiang Huang,
Chao-Cheng Lan, and Chi-Chuan Wang

Department of Mechanical Engineering
National Chiao Tung University
Taiwan, R. O. C.

Principles:


+
V
-
collector
electrode
corona
electrode
ionization zone
drifting zone


Corona
electrode
Collector
electrode

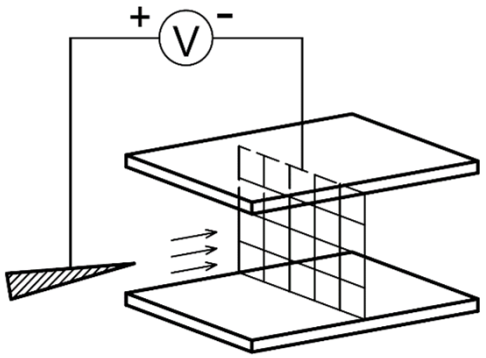
Applications (1)

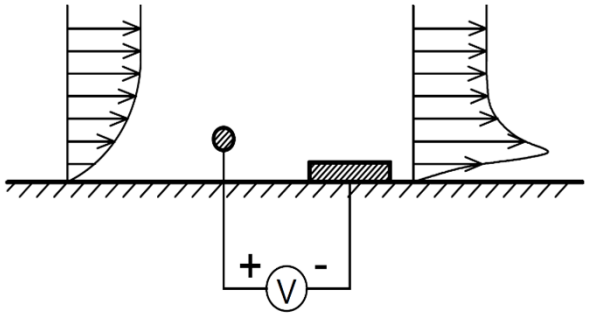
- Existent applications of the corona discharge

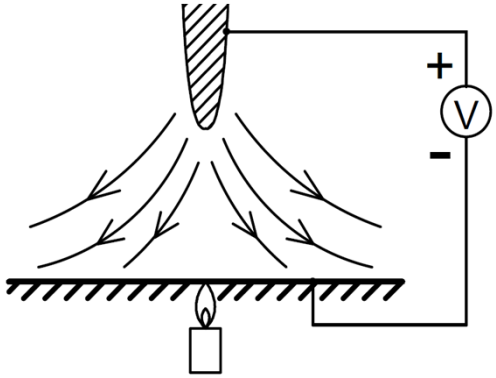
  electro-photographic printing (xerography)
  electrostatic precipitator (ESP)

Applications (2): use of ionic wind

- Recent interests and research
  micro-pumps
  heat transfer enhancement
  food drying and bio-processing
  boundary layer regulation



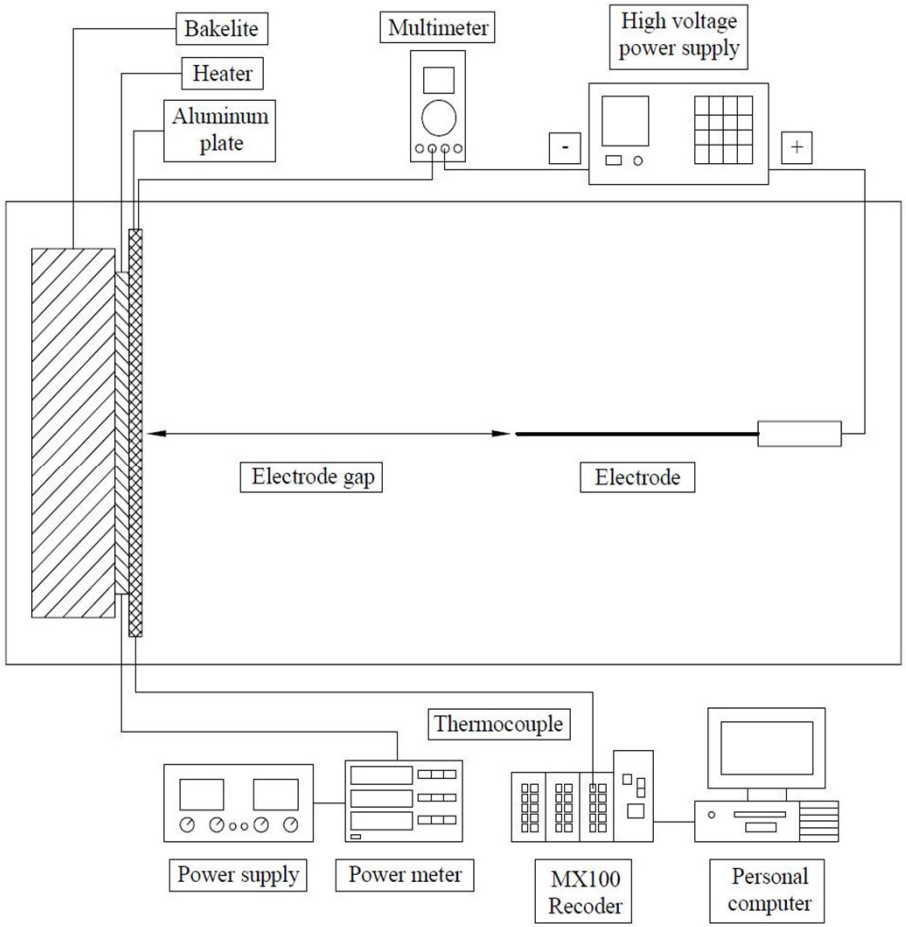




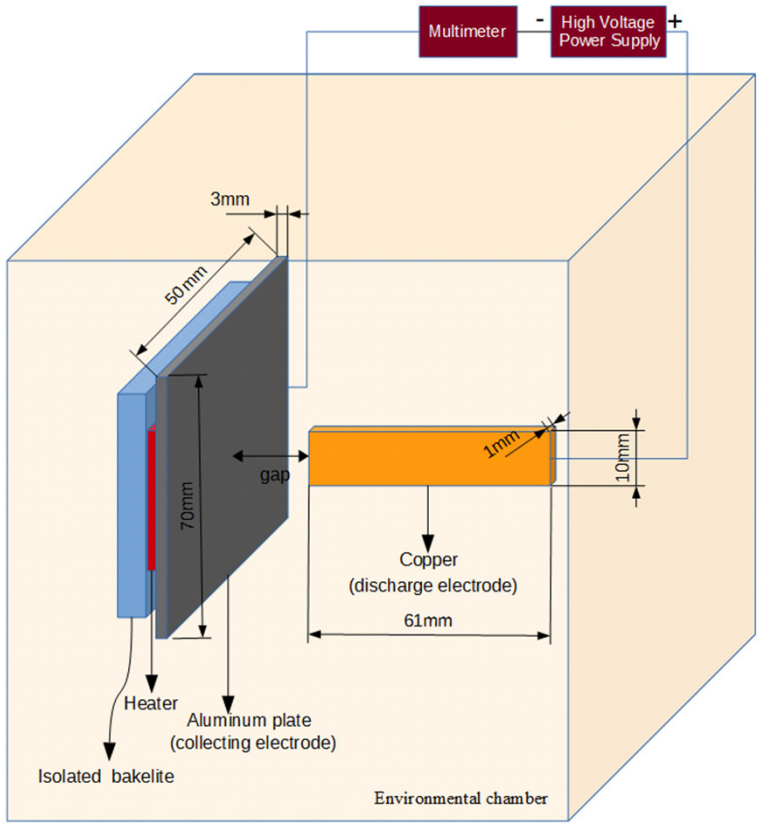
Advantages and disadvantages

- Pros:
  - no moving parts
  - silent operation
  - little power consumption
  - small scale in size
- Cons:
  - poor electric-to-fluid energy conversion
  - ozone production
  - degradation of electrodes over time
  - high voltage

Experimental setup (1)



Experimental setup (2)



Modeling for electric field

$$\nabla^2 \varphi = -\nabla \cdot \vec{E} = -\frac{q}{\varepsilon}\varphi$$

$$where \quad \vec{E} = -\nabla \varphi$$

$$\frac{\partial q}{\partial t} + \nabla \cdot \vec{J} = 0$$

$$where \quad \vec{J} = \mu_E \vec{E} q + \vec{V} q - D \nabla q$$

$$[drifiting] \quad [convection] \quad [diffusion]$$

Modeling for flow field

$$\nabla \cdot \vec{V} = 0$$

$$\frac{\partial \rho \vec{V}}{\partial t} + \nabla \cdot (\rho \vec{V} \otimes \vec{V}) = -\nabla P + \mu \nabla \cdot \nabla \vec{V} + \vec{F}$$

$$where \quad \vec{F} = q\vec{E} - \frac{1}{2}\left|\vec{E}\right|^2 \nabla \varepsilon + \frac{1}{2}\nabla\left(\rho \frac{\partial \varepsilon}{\partial \rho}\left|\vec{E}\right|^2\right)$$

$$\begin{bmatrix} Coulomb \\ force \end{bmatrix} \begin{bmatrix} dielectrophoretic \\ force \end{bmatrix} \begin{bmatrix} electrostrictive \\ force \end{bmatrix}$$

$$\frac{\partial \rho C_P T}{\partial t} + \nabla \cdot (\rho \vec{V} C_P T) = \nabla \cdot (\mathrm{k} \nabla T) + \sigma_E \left|\vec{E}\right|^2$$

$$[Joule \quad heating]$$

Boundary conditions for electric field

- Applied voltage on the discharge electrode and zero voltage on the collecting electrode
- I-V relationship determined from experiments for the charge density at the discharge electrode

$$I = \int_S \vec{J} \cdot d\vec{s} = \int_S \mu_E \vec{E}_{onset} q \cdot d\vec{s}$$

- Peek's formula

$$E_{onset} = E_0 (1 + 2.62 \times 10^{-2} / R_w)$$

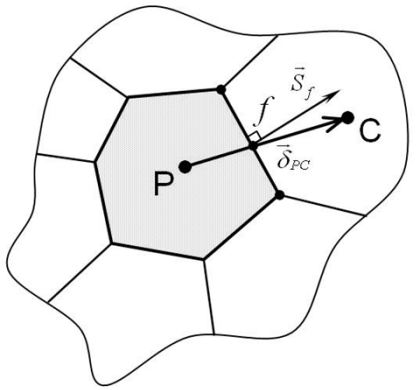
E_0 : Kaptzov's constant

Numerical Methods

- General form of the equations

$$\frac{\partial \phi}{\partial t} + \nabla\cdot(\vec{V}^{*}\phi) = \nabla\cdot(\Gamma\nabla\phi) + S_{\phi}$$

- Discretization by the finite volume method suitable for use of unstructured grids of arbitrary geometry
- Convection flux: hybrid scheme of UD/2nd order UD
- Diffusion flux: over-relaxed scheme



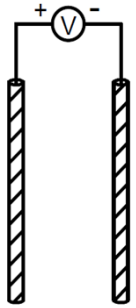
Ref: Y.-Y. Tsui and Y.-F. Pan, Numerical Heat Transfer B, 49 (2006) 43-65

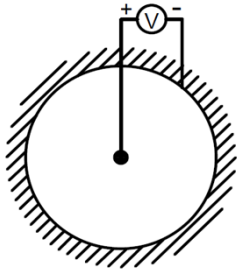
Verification (1)

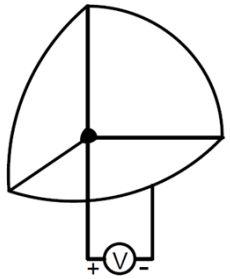
- Benchmark problems for corona discharge

$$\frac{1}{r^n}\frac{\partial}{\partial r}\left(r^n\frac{\partial\varphi}{\partial r}\right)=-\frac{q}{\varepsilon}$$

$$\frac{1}{r^n}\frac{\partial}{\partial r}\left(\mu_E r^n\frac{\partial\varphi}{\partial r}q\right)=0$$







where n=0: planar 1-D

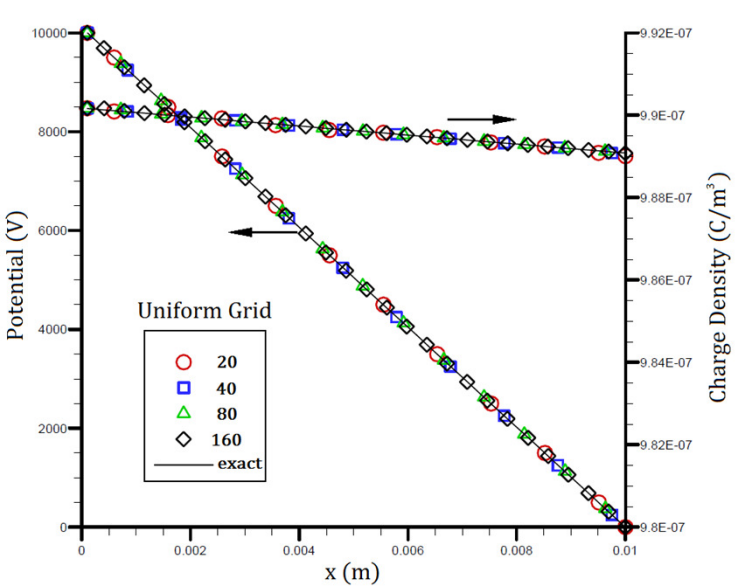
n=1: axisymmetric 2-D

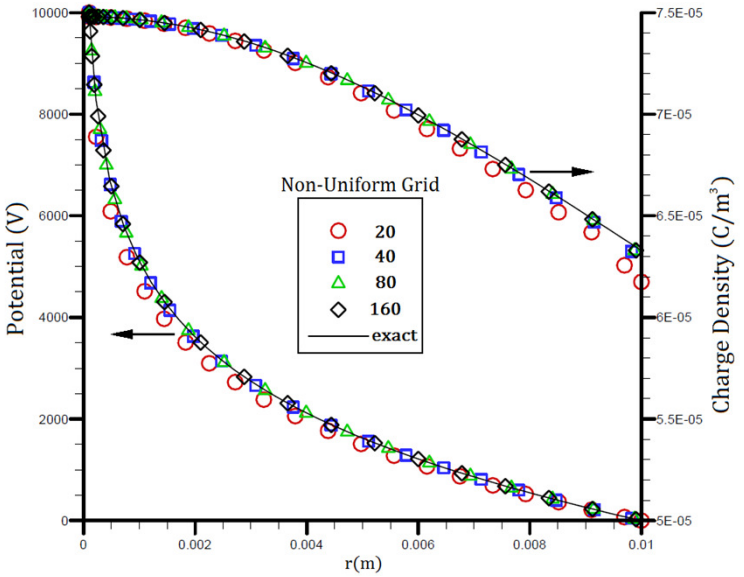
n=2: spherically symmetric 3-D

Analytical solutions: closed form solutions for the 1-D and 2-D problems

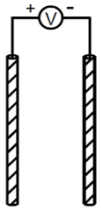
numerical solution by the Runge-Kutta method for the 3-D problem

Verification (2)

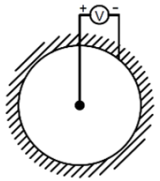




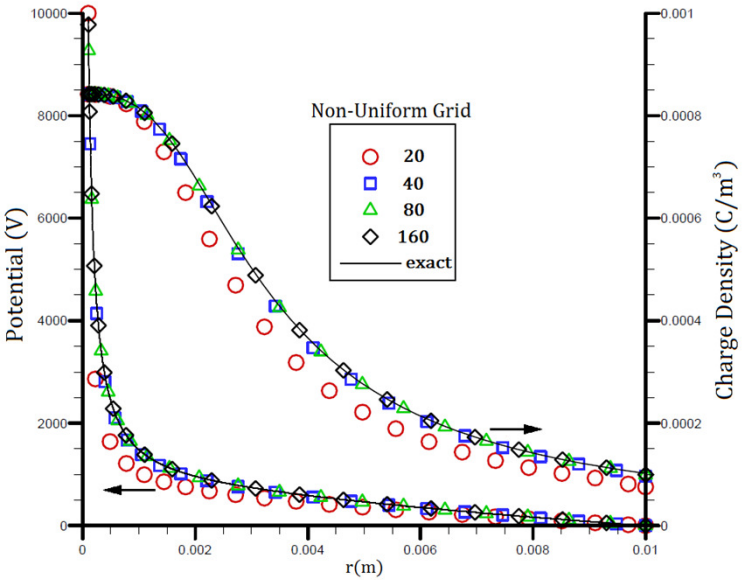
Planar 1-D



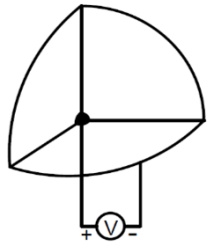
Axisymmetric 2-D



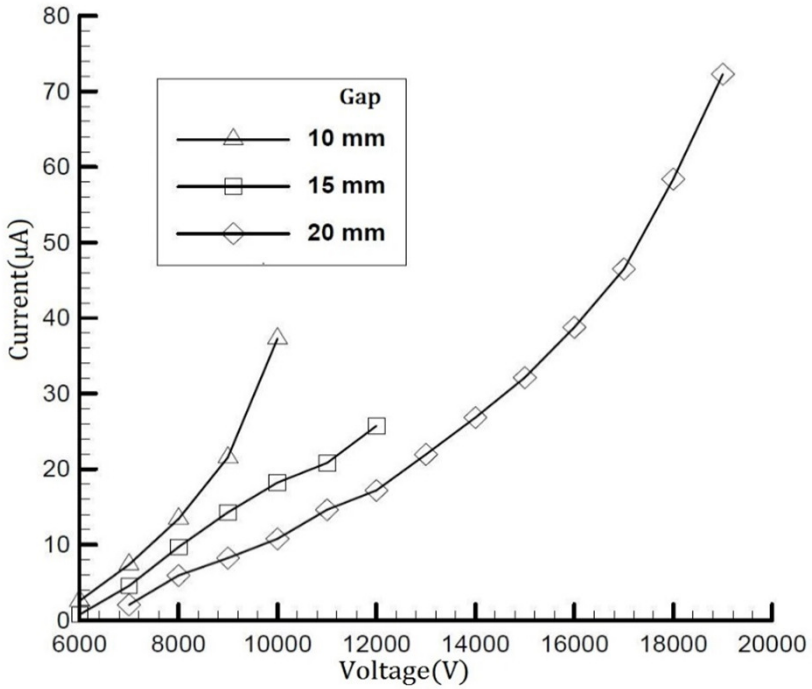
Verification (3)



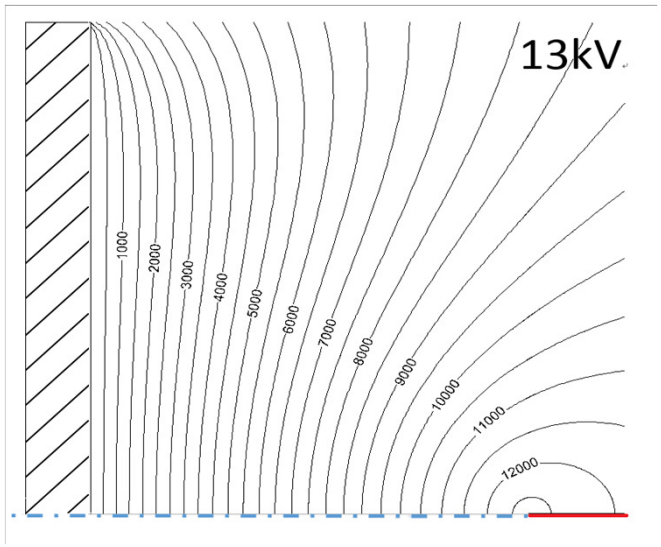
Spherically symmetric 3-D



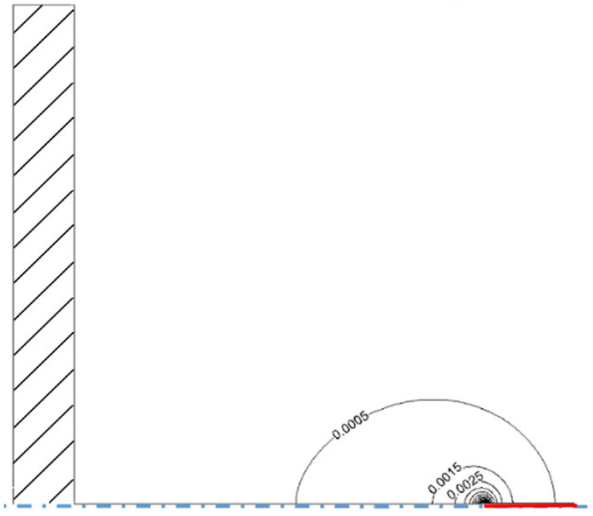
Current-voltage (I-V) relationships



Simulating results (1)

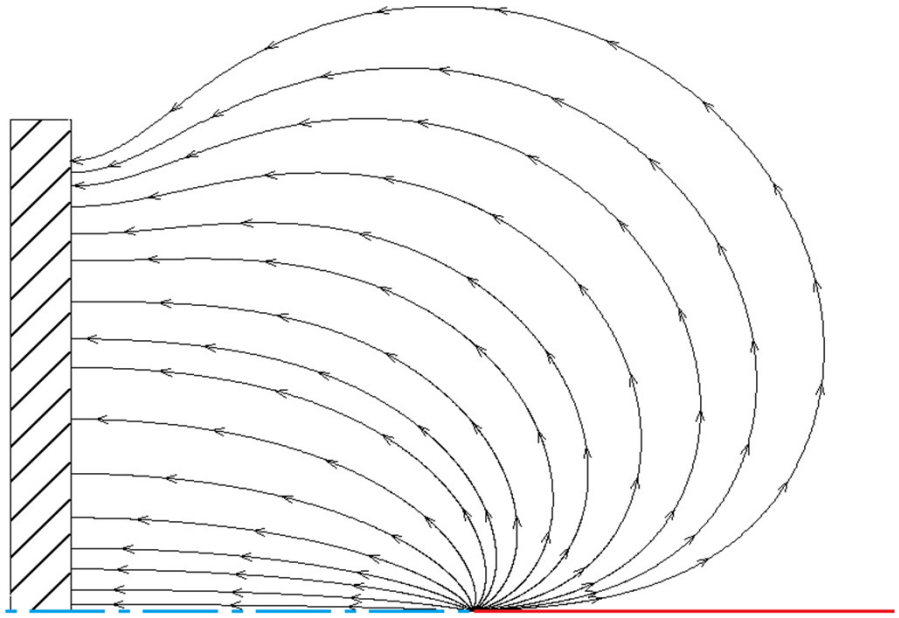


potential



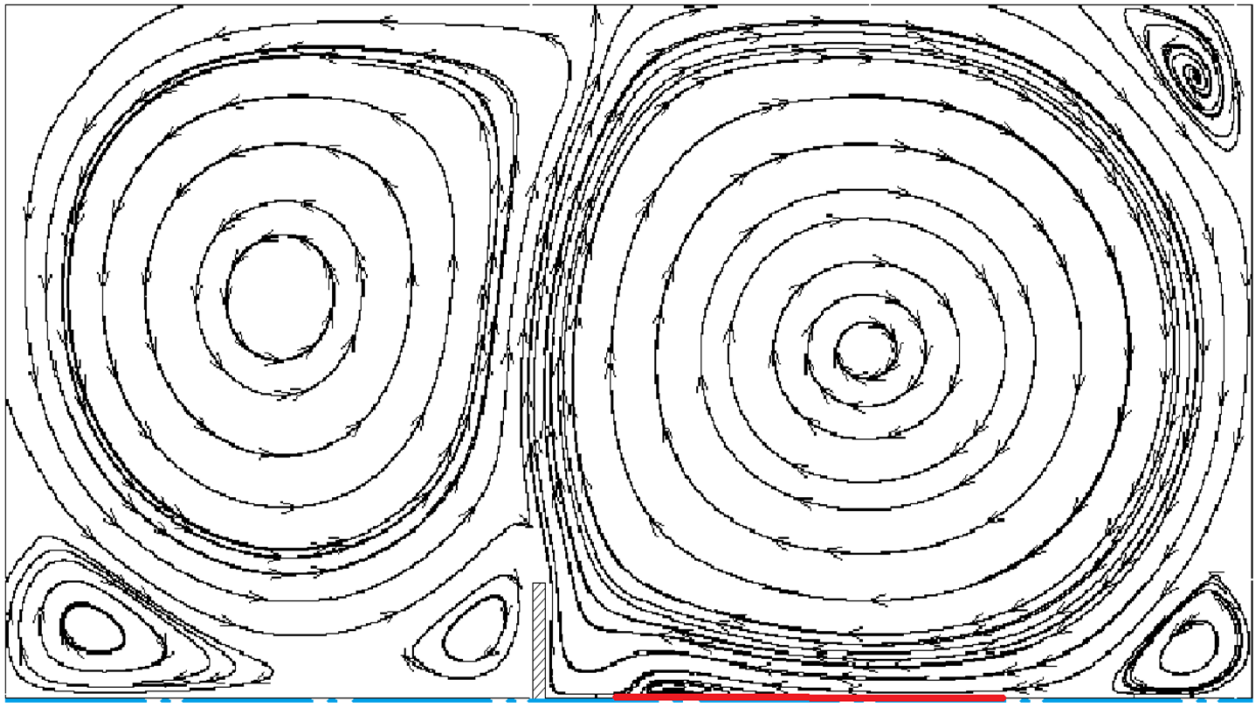
charge density

Simulating results (2)



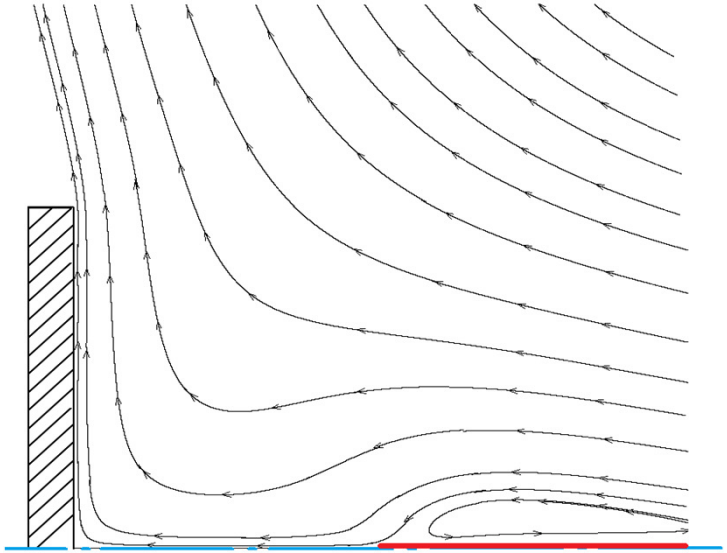
electric field lines of force

Simulating results (3)

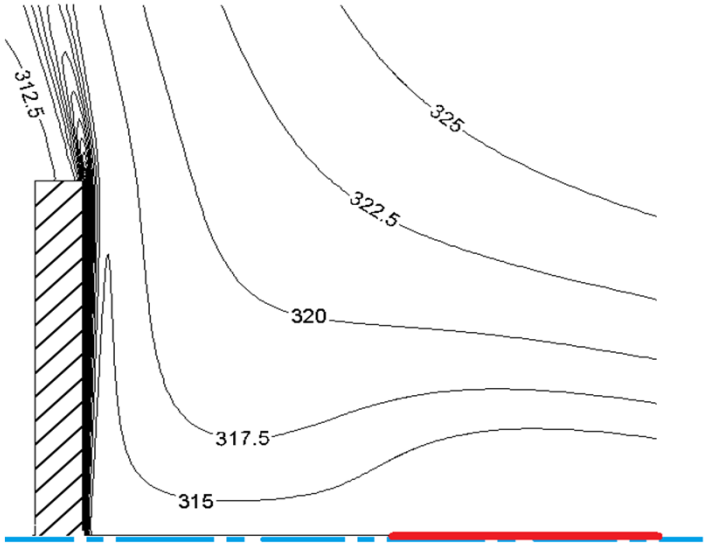


flow streamlines in the chamber

Simulating results (4)

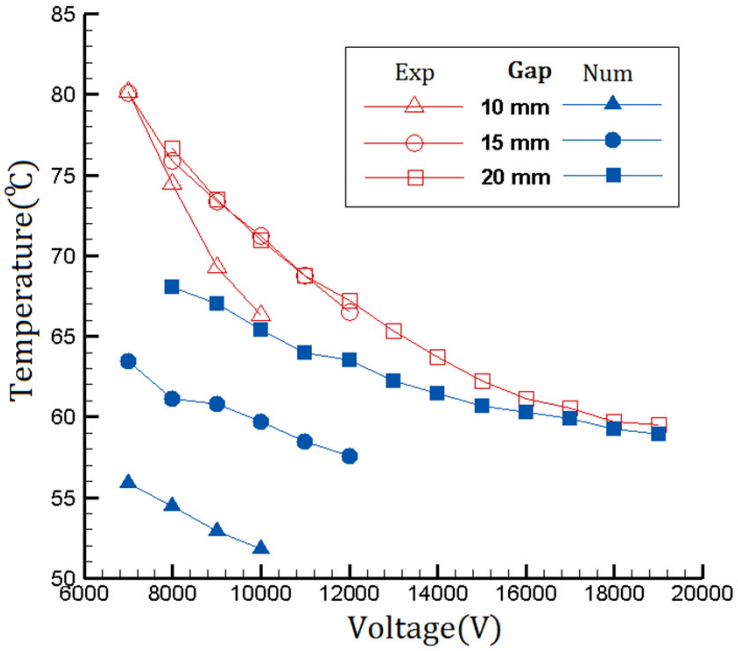


streamlines

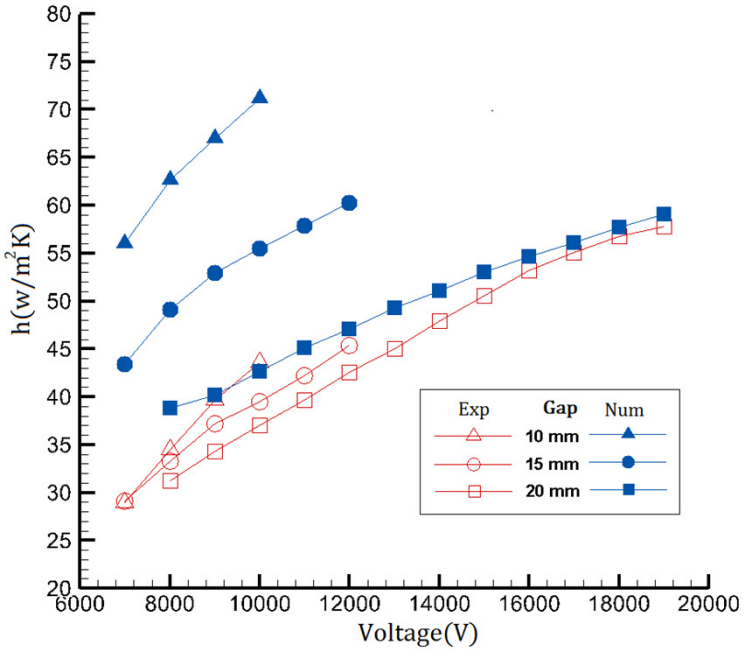


temperature

Comparison of predictions and measurements

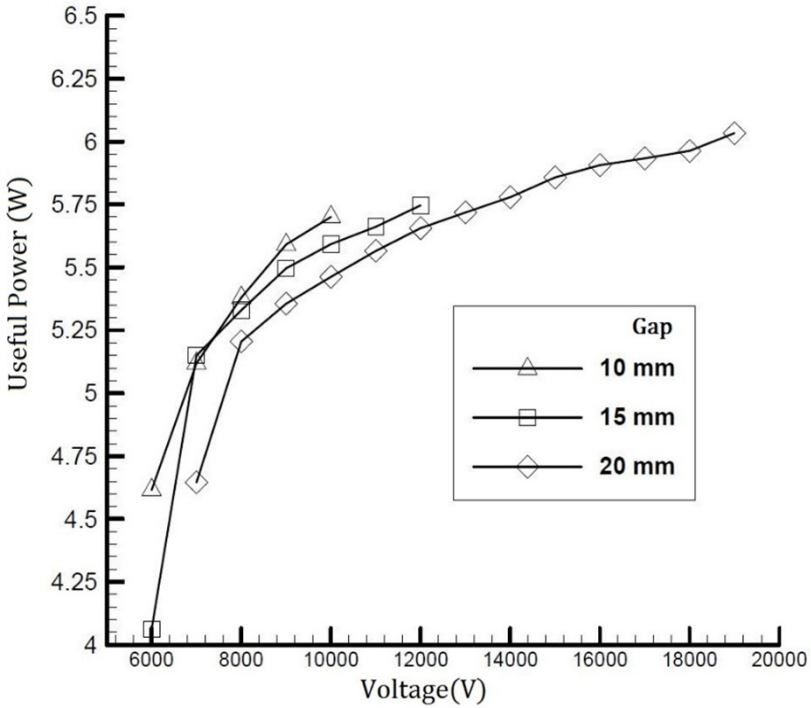


Temperature at the center of the collecting plate



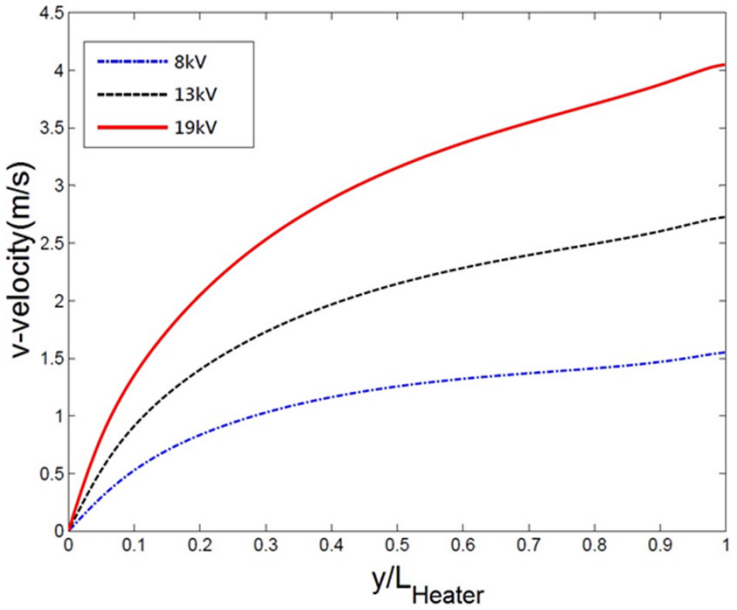
Heat transfer coefficient

Actual power for heating

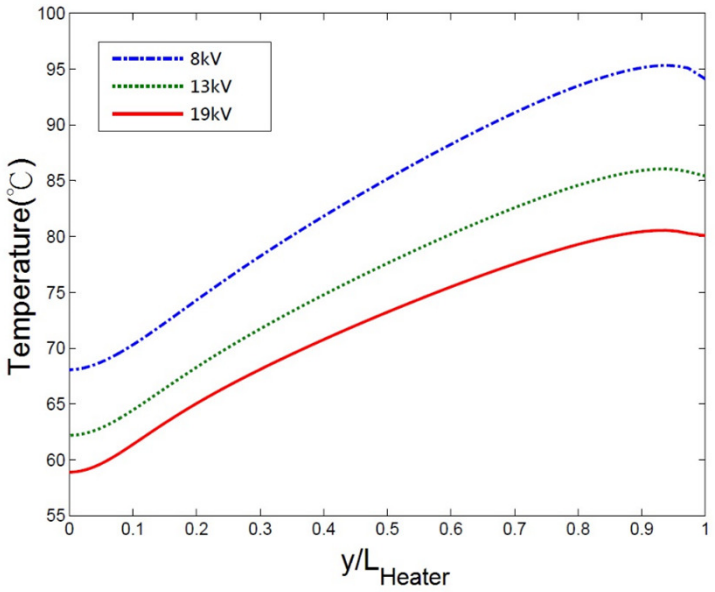


- A constant power of 7.5 W is supplied for heating.

Effects of stagnation flow on heat transfer



Distribution of v-velocity near the collecting plate



Temperature distribution on the collector plate

Concluding remarks

- Comparison of numerical and analytic solutions for benchmark problems shows very good agreement obtained.
- A jet-like flow is induced by the corona discharge to form a stagnation flow over the collecting plate. Heat transfer is then enhanced.
- The corona effect is more effective for small inter-electrode gaps. However, the maximum allowed voltage is higher when the electrode gap is large. Therefore, optimization on the applied voltage and electrode gap is necessary.
- The differences between predictions and measurements is mainly attributed to heat loss from the heater not accounted for in calculations, which is high at low applied voltages, but low at high applied voltages.

Finale

Thanks