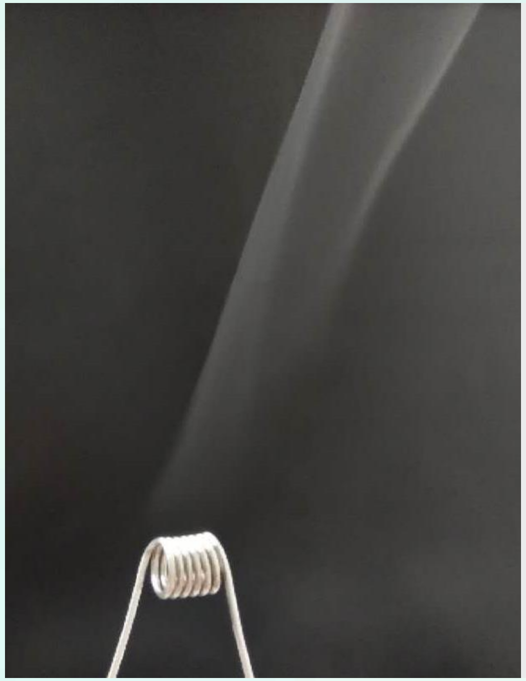

Study on capillary-evaporation effect in porous medium of electronic cigarettes

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CONTENT

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1. Introduction

Why?

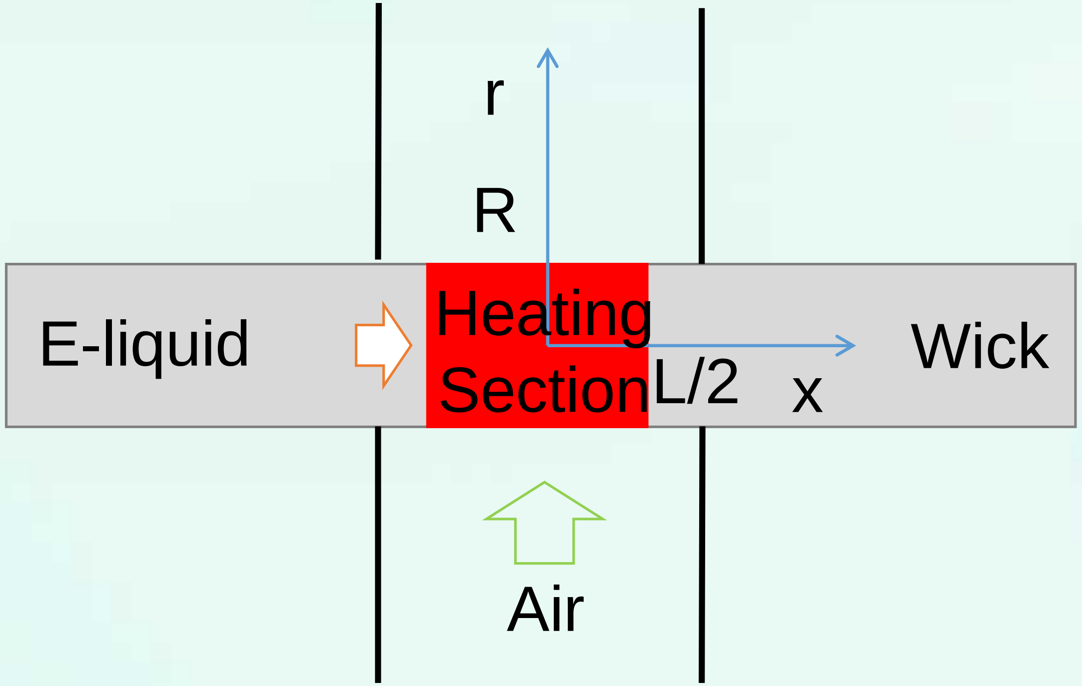
Product development is a trial-and-error approach

Principles of heat and mass transfer

Provide theoretical basis for product development

Effectively guide product development

2. Theoretical Model



1.Heat transfer?

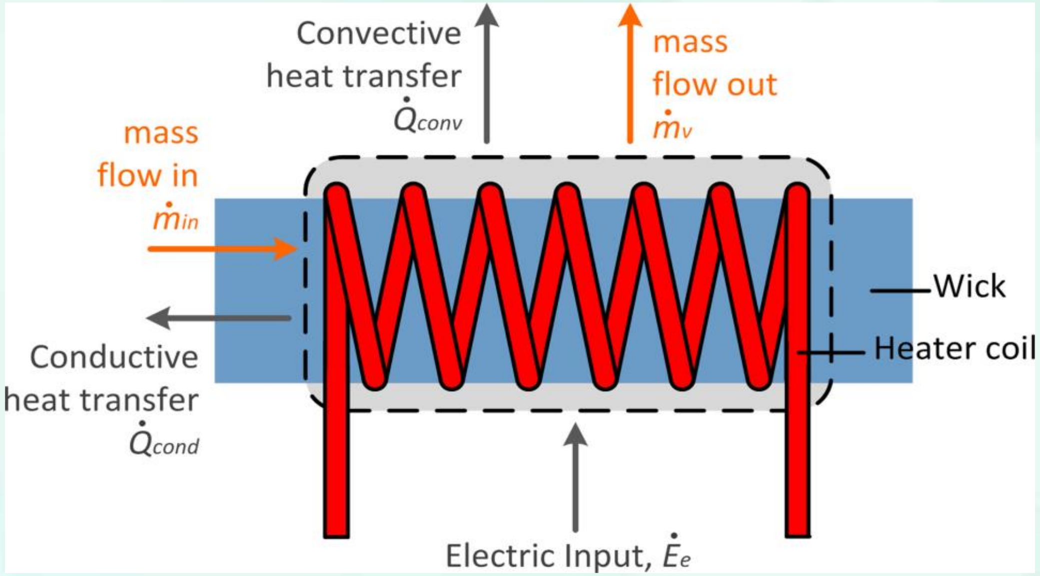
2.Mass(e-liquid) transfer?

The schematic diagram of wick for electronic cigarettes
(the red area represents heating section, i.e. where the coil is wound)

2. Theoretical Model

2.1 Unsteady energy equation

— zero dimensional model of heating zone
— compute the instantaneous temperature



$$C\frac{dT}{dt}=\dot{E}_e-(\dot{Q}_{conv}+\dot{Q}_{cond}+\dot{Q}_{liq}+\dot{Q}_{lat})$$

C is the effective heat capacity; E_e is the electrical power input to the device

Q_{conv} is the rate of heat transfer by convection to the air flowing

Q_{cond} is the rate of heat transfer by conduction through the wick and electrical leads

Q_{liq} is the energy expended heating the liquid

Q_{lat} is the latent heat associated with change of phase from liquid to vapor

2. Theoretical Model

2.2 Conservation of mass equation

— zero dimensional model of heating zone

— Compute instantaneous composition of the remaining e-liquid

$$\frac{dm_i}{dt} = m_{liq}\frac{dw_i}{dt} = \dot{m}_{\mathrm{t,i}} - \dot{m}_{v,i}$$

Average evaporation rate

M_{liq} is the total mass of the remaining liquid, mg;

W_{i} is the mass fraction of component I in the remaining liquid;

$M_{\mathrm{t,i}}$ is the transport velocity of liquid component I, mg/s;

$M_{\mathrm{v,i}}$ is the evaporation rate of liquid component I, mg/s.

2. Theoretical Model

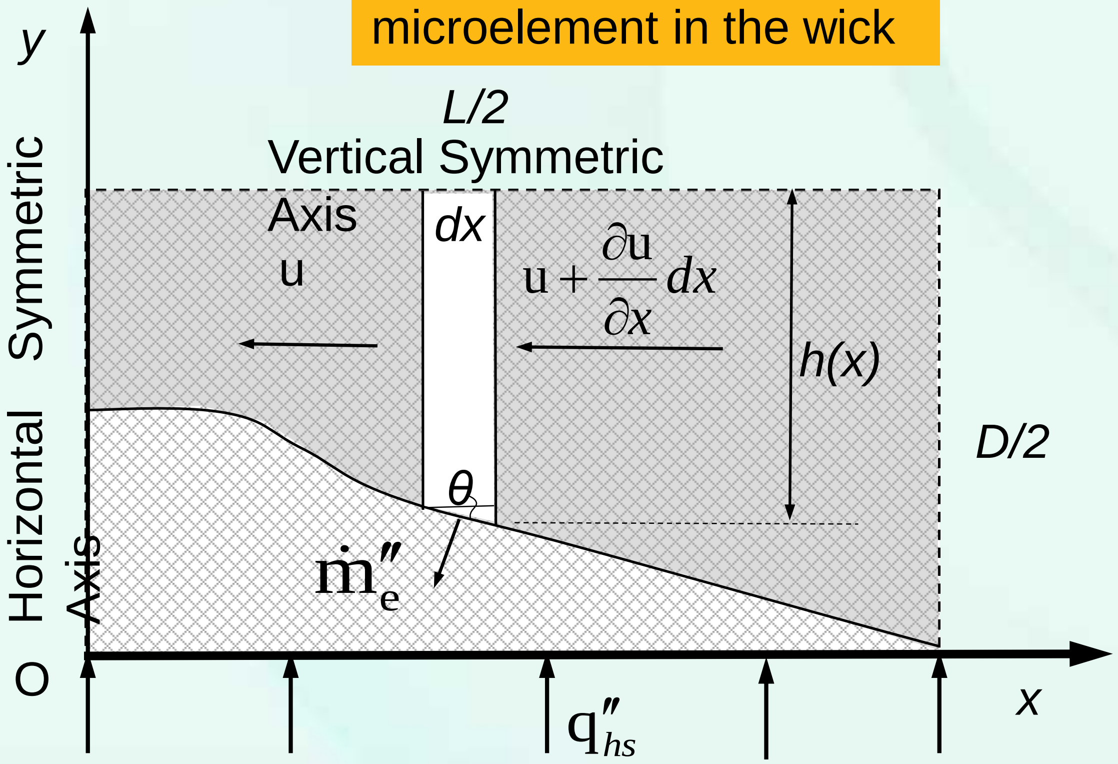
2.3 Mass equation of a microelement

— One dimensional capillary transport model

$$\int_0^{\delta} \rho u \varepsilon dy = \int_0^{\delta+\frac{d\delta}{dx}\cdot dx} \rho\left(u+\frac{\partial u}{\partial x}dx\right)\varepsilon dy + \dot{m}''_e \cdot dx$$

- Seepage rate of e-liquid
- Saturation distribution

Schematic diagram of a microelement in the wick



3. Experimental Bench and Methods

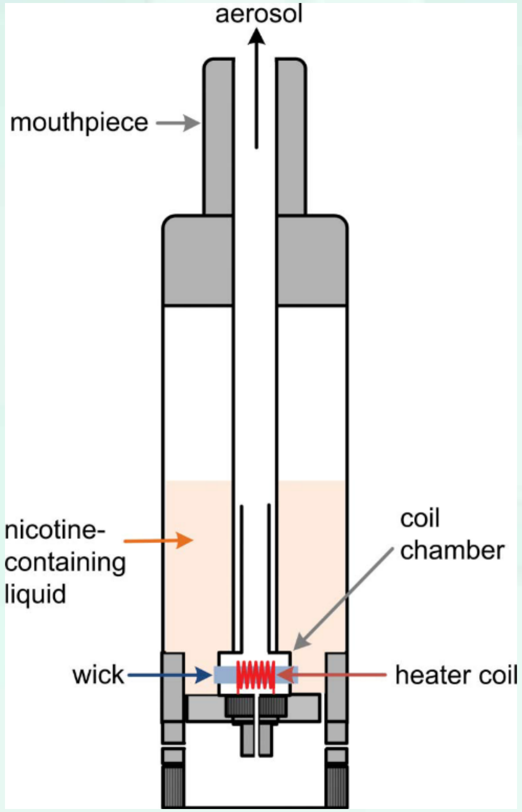
The geometric size of electronic cigarette is small

Cause

Testing the parameters of electronic cigarettes is difficult

Base on similarity theory

Designing and building a scaled-model experimental bench



[1] Talih S , Balhas Z , Salman R , et al. Transport phenomena governing nicotine emissions from electronic cigarettes: Model formulation and experimental investigation[J]. Aerosol Science and Technology, 2017, 51(1):11.

3. Experimental Bench and Methods

The similarity conditions of two similar physical phenomena

(1) The definite featured numbers with the same name are equal;

(2) The single valued conditions are similar.

The similarity criteria of scaled-model experiment for electronic cigarettes

Dimensionless Number	Reynolds Number	Prandtl Number	Nusselt Number	Fourier Number
Dimensionless Equation	$\mathrm{Re} = \frac{ul}{\upsilon}$	$\mathrm{Pr} = \frac{\mu c_p}{\lambda}$	$Nu = \frac{hl}{\lambda}$	$Fo = \frac{a\tau}{l^2} = \frac{\lambda}{\rho c}\frac{\tau}{l^2}$

3. Experimental Bench and Methods

Comparison of geometric dimension parameters

Pattern	Length of wick/mm	Diameter of wick/mm	Winding diameter of coil/mm	Diameter of coil/mm	Winding number of coil	Inner diameter of airflow channel/mm
Prototype electronic cigarette	**16**	**3**	**3**	**0.5**	**5**	**8**
Scaled-model experimental bench	**80**	**15**	**15**	**0.5**	**25**	**40**

3. Experimental Bench and Methods

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Comparison of working parameters

Pattern	Puffing flow velocity/(m/s)	Puffing flow rate/(mL/s)	Puffing time/s	Puffing interval/s	Puffing curve	Heating power
Prototype experiment	0.36	18.3	3	30	Square wave	P
Model experiment	0.07	91.5	75	750	Square wave	5P

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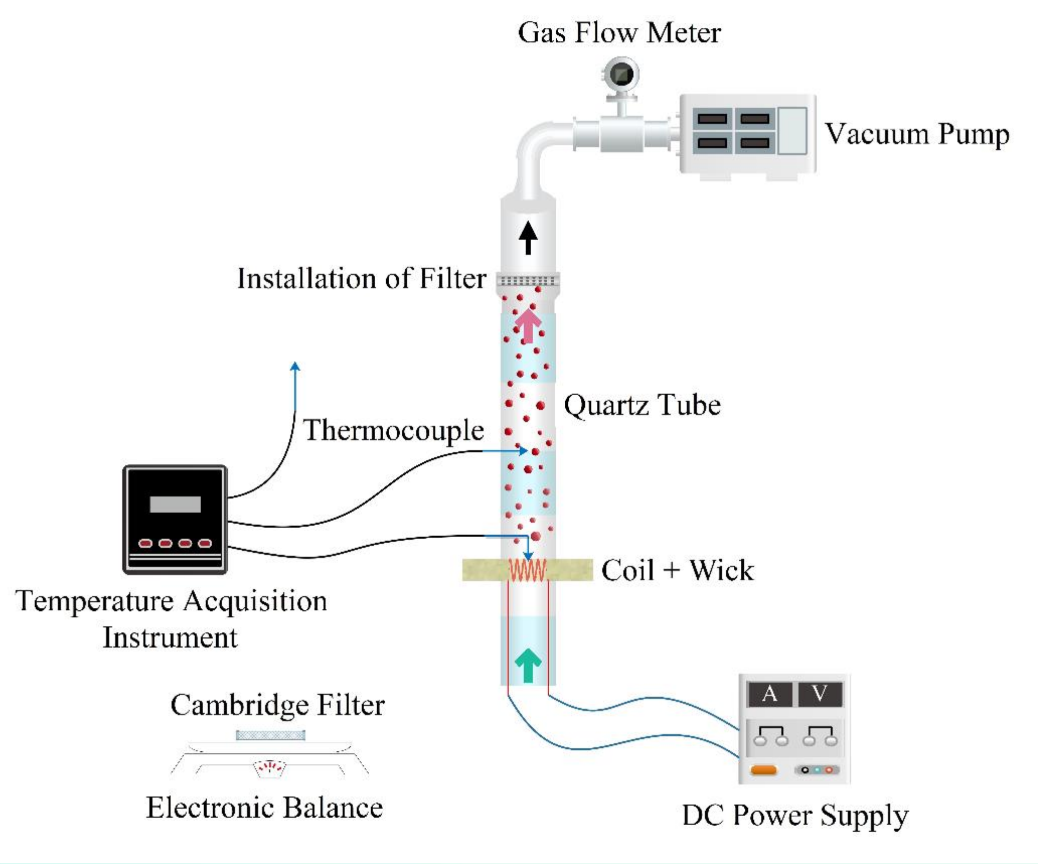
3. Experimental Bench and Methods



The schematic diagram of scaled-model experimental bench for electronic cigarettes

Cambridge Filter	Trapping Aerosol Particles
Coil + Wick	Acting as The Electronic Cigarette Atomizer
DC Power Supply	Adjusting Output Power
Temperature Acquisition Instrument + Thermocouple	Collecting Atomization Temperature
Vacuum Pump + Gas Flow Meter	Adjusting Puffing Flow Rate

3. Experimental Bench and Methods

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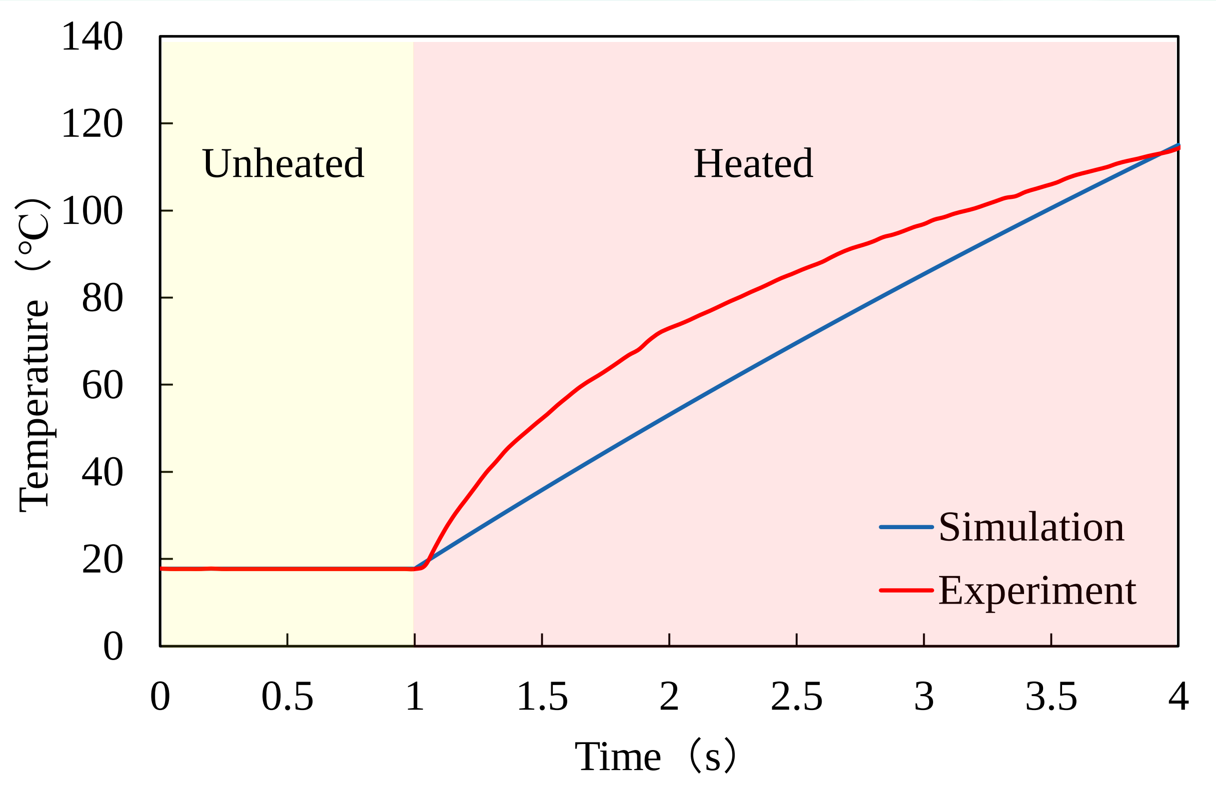
The similarity relation of heating power

E-liquid	PG					VG					PG:VG=1:1(VOL)				
Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Prototype	1.46	2.40	3.50	5.32	8.32	1.46	2.50	4.73	6.64	8.32	1.36	2.40	4.56	6.58	9.09
Scaled-model	7.28	12.00	17.52	26.60	41.60	7.28	12.50	23.64	33.18	41.6	6.80	12.00	22.80	32.90	45.44

4. Results and Discussion

4.1 Measured vs Computed

- Simulation = average temperature of the heating zone
- Experiment =operating temperature of heating coil
- The energy is mainly contributed to the heating of coil (early stage) and vaporization (late stage).



Comparison of **temperature of coil** between simulation and experiment. VG, 2.5W, 18.33mL/s, 3s)

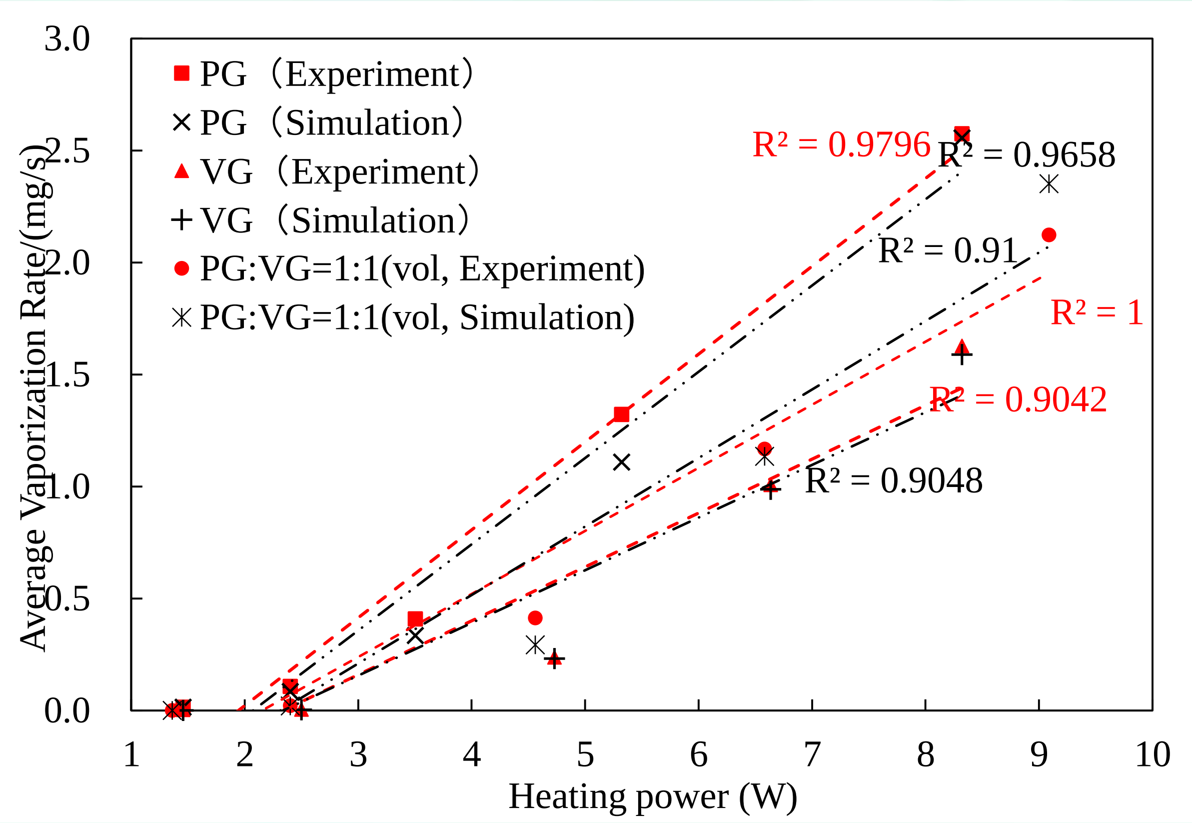
4. Results and Discussion

4.1 Measured vs Computed

a. Average vaporization rate and heating power are positively linearly correlated (2W-9W);

b. At the same heating power, average vaporization rate: PG > PG&VG> VG

Specific Heat Capacity（sensible heat） & heat of vaporization (latent heat)
PG＜VG



The variation characteristic of **average vaporization rate** with heating power from 1 to 10 W

4. Results and Discussion

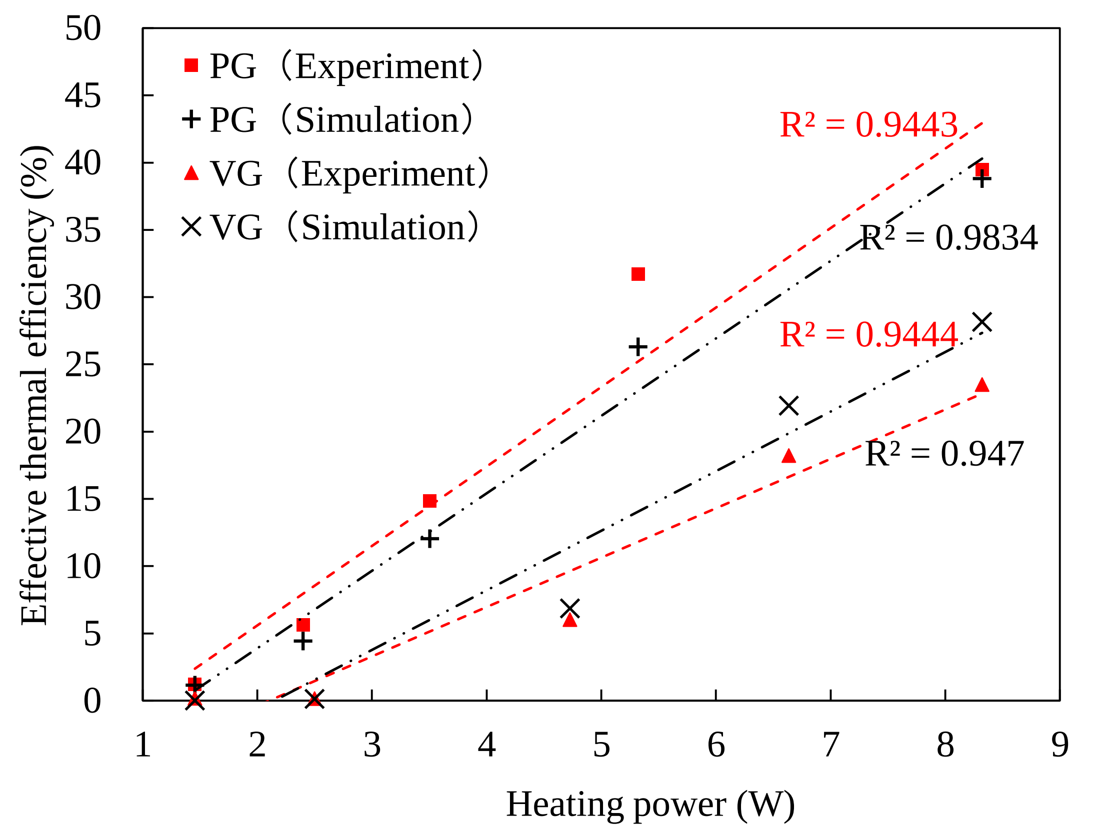
4.1 Measured vs Computed

Effective Thermal Efficiency:

Effective heat consumption in e-liquid vaporization process

(Sum of Sensible Heat and Latent Heat) / Total supply heat

- Linear positive correlation
- PG > VG

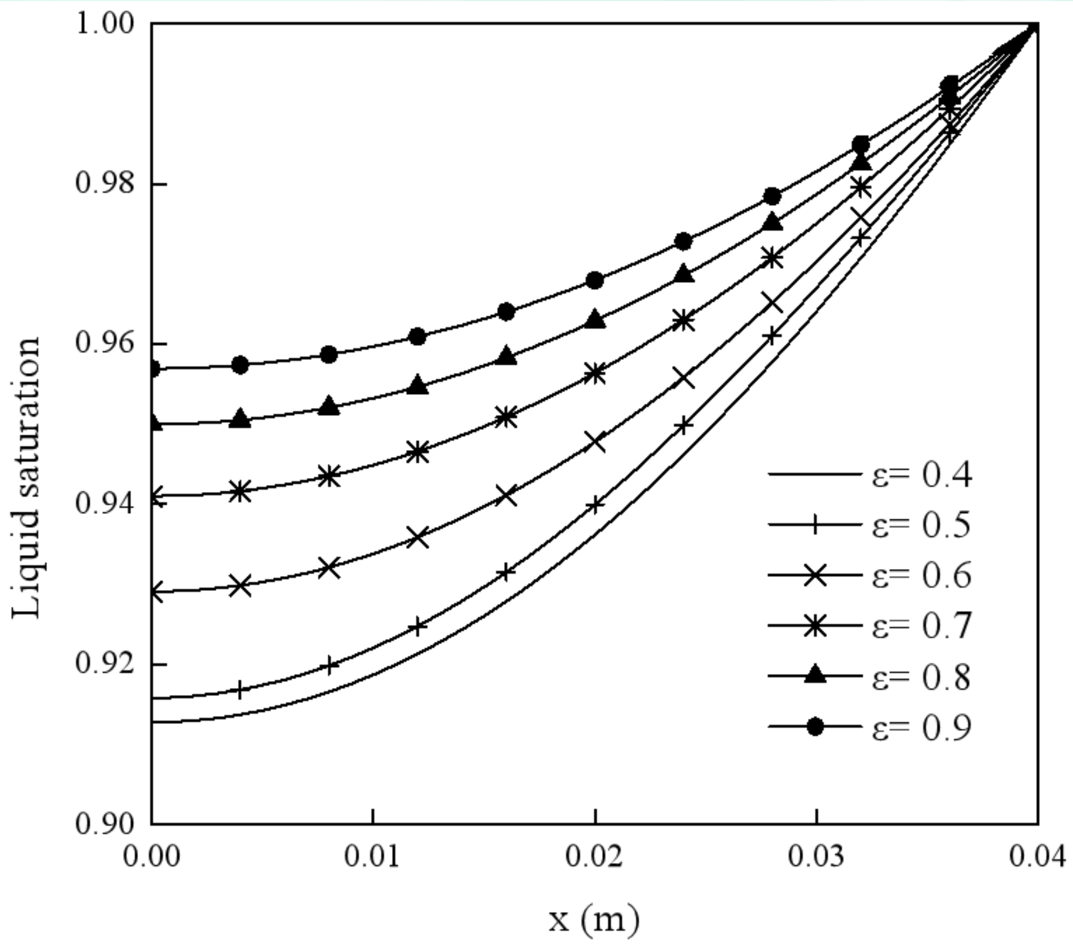


The variation characteristic of **effective thermal efficiency** with heating power for PG and VG

4. Results and Discussion

4.2 The influence factors of liquid saturation and its transport rate

- Saturation increases with porosity.
- The further away from the heating centre, the greater the saturation.



Effect of **porosity** on **saturation distribution** in the heated section of wick (PG, 2.5W, 0.1s)

4. Results and Discussion

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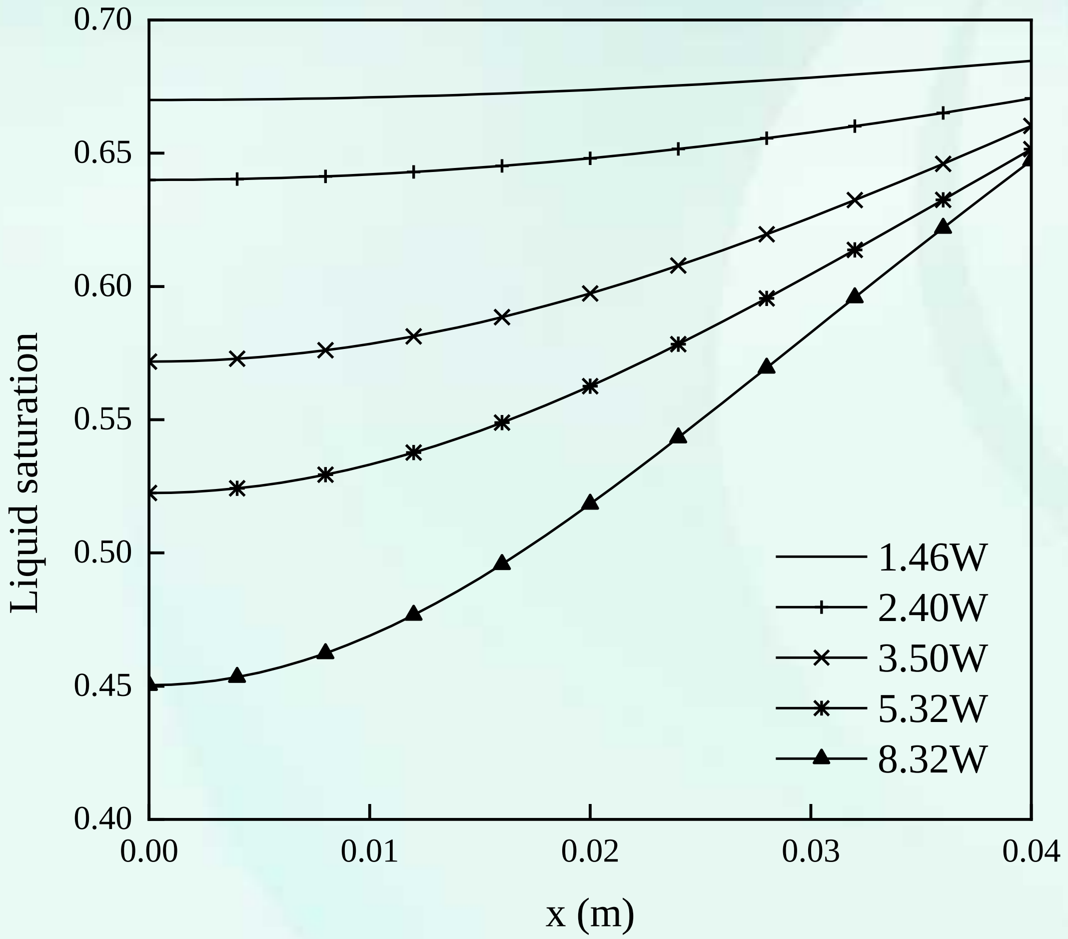
4.2 The influence factors of liquid saturation and its transport rate

- Saturation decreases as power increases.
- The centre of heating zone is prone to dry heating.

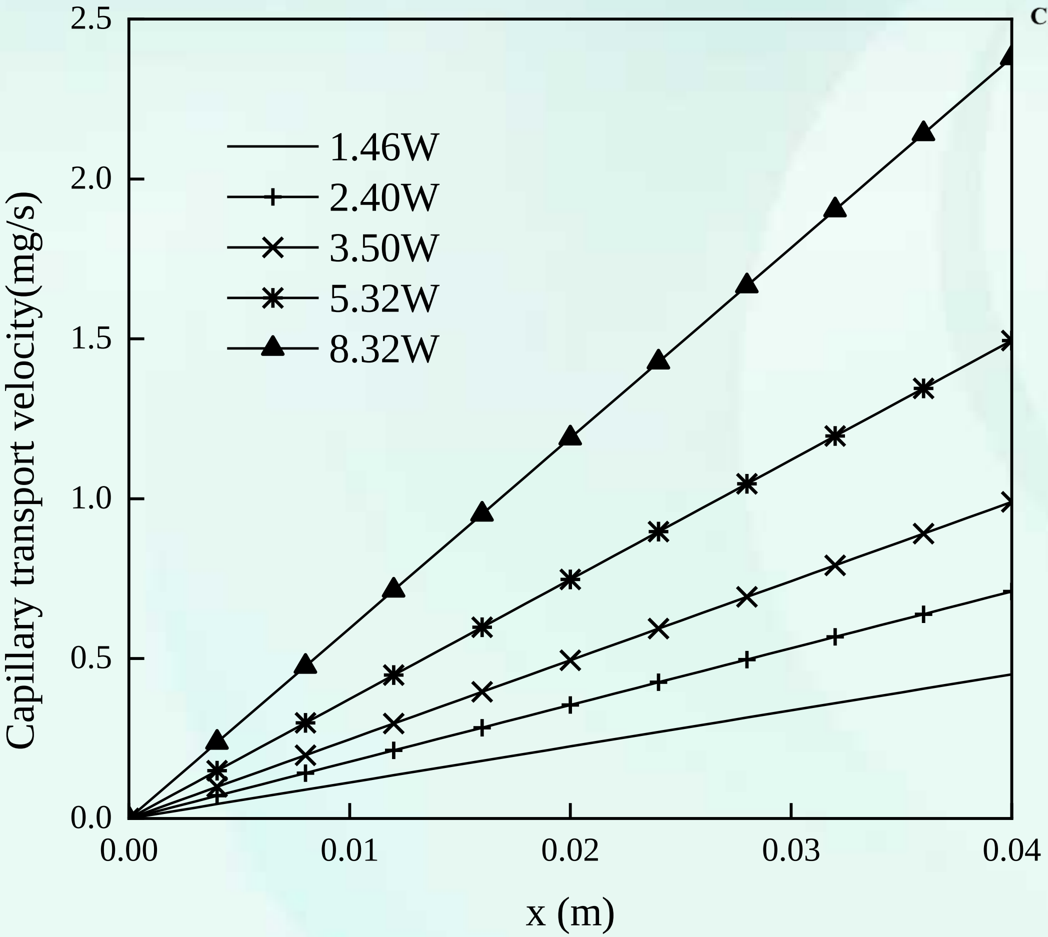


Effect of heating power on **saturation distribution** in the heated section of wick (E-liquid: PG, Porosity: 0.5, Time: 3.0s)

4. Results and Discussion

4.2 The influence factors of liquid saturation and its transport rate

With the increase of heating power, the gradient of saturation (concentration difference) at the same position increases.



Effect of heating power on **capillary transport velocity** in the heated section of wick (E-liquid: PG, Porosity: 0.5, Time: 3.0s)

5. Conclusions

The average vaporization rate and effective vaporization heat efficiency increased linearly with the incremental increase of the heating power.

Applying the same heating power and puffing regime, a higher PG content in the e-liquid resulted in a greater vaporization rate and aerosol mass concentration.

The heat efficiency (at same heating power) of PG was higher than that of VG.

5. Conclusions

As porosity of the wick increases, the e-liquid saturation level increases, leading to a reduced likelihood of dry heating.

The transport rate of e-liquid at the beginning of the heating zone was higher than rate in the center, therefore dry heating was most likely to occur at the center of heating zone.

The e-liquid saturation level in the heating zone decreased with the increase of the heating power. A higher heating power will therefore increase the probability of dry heating.

Thank you for your attention