# Another possible origin of temperature and pressure gradients across vanes in the Crookes radiometer

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Aug 18, 2017



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# **The Crookes Radiometer** [1,2]

- 4 vanes in a glass bulb partially evacuated.
- One side of vane is black and the other side is shiny.
- Vanes revolve with shiny side leading under sunlight.





#### **Past Simulation Studies** [3-10]

- Great efforts made by many researchers to reveal forces on vanes
  - thermal transpiration / thermal creep force due to  $\Delta T$
  - area force by  $\Delta p$
- Assumptions used in every work
  - temperature at black side of vane is higher than that at the shiny side,  $T_{\rm B} > T_{\rm S}$ .
  - accommodation coefficient  $\alpha$  is uniform and same at both sides of vane.



# New Hypothesis proposed in This Study

- Vanes is **isothermal at**  $T_{\rm V}$ .
- Accommodation coefficient  $\alpha_{\rm B}$  at black side of vane is different from that at shiny side  $\alpha_{\rm S}$ , and  $\alpha_{\rm B} > \alpha_{\rm S}$ .





# **Estimating Vane Temperature**

Heat balance equations under Biot number  $Bi \ll 1$ •

$$\begin{cases} q_{\rm in} - (q_{\rm g,B}^t + q_{\rm r,B}^t) = -\kappa \frac{\partial T_{\rm V}^t}{\partial x} \\ \rho L_{\rm b} C_{\rm p} \frac{\partial T_{\rm V}^{t+\Delta t}}{\partial t} = q_{\rm in} - (q_{\rm g,B}^t + q_{\rm r,B}^t) - (q_{\rm g,S}^t + q_{\rm r,S}^t) \\ q_{\rm g,B/S}^t = \frac{1}{4} n \bar{v} \Delta E = \frac{1}{2} n k \sqrt{\frac{8kT_{\rm g}}{\pi m}} (T_{\rm V,B/S}^t - T_{\rm g}) \\ q_{\rm r,B/S}^t = \varepsilon_{\rm B/S} \sigma \left\{ (T_{\rm V,B/S}^t)^4 - T_{\rm g}^4 \right\} \\ \frac{Material Properties [11-14]}{\rho (\rm kg/m^3) - C_{\rm p} (\rm J/\rm kg-\rm K) - \kappa (W/m-\rm K) - \epsilon} \end{cases}$$

	$\rho$ (kg/m)	$C_p(J/Kg-K)$	K (W/III-K)	5
A1	2688	905	237	0.17
Mica	2100	880	0.5	0.72
Soot	100	1000	0.05	0.95



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#### **Estimating Vane Temperature (cont'd)**

- Typical heat flux of sunlight is  $700 1400 \text{ W/m}^2$  [15,16]
- Calculated Biot number Bi < 0.01.
- Vane is isothermal under sunlight.

![](_page_5_Figure_4.jpeg)

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![](_page_6_Picture_0.jpeg)

- Multipurpose 2D DSMC software created on MS-Excel
  - www2b.biglobe.ne.jp/~denpoh/Software/DSMC\_xls/
- Gas (Air)
  - Diatomic molecule with rotational degrees of freedom
  - Molecular model: Maxwell molecule
  - Collision models: VHS model, Larsen-Borgnakke model
- Accommodation coefficients
  - Black side:  $\alpha_{\rm B} = 1$  (diffuse reflection)
  - Shiny side: diffuse reflection  $\alpha_{\rm S}$  + specular reflection  $(1 \alpha_{\rm S})$

![](_page_6_Picture_10.jpeg)

![](_page_6_Picture_11.jpeg)

# Model Setup in DSMC\_2D.xls

• Vane length  $L_a = 13$  mm, thickness  $L_b = 2$  mm

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3	Cells	d×	1.00E-03	m	Cell size in I-direction
4		dy	1.00E-03	m	Cell size in J-direction
5					
6	Gas Properties	Molecular Weight	28.970	g/mol	
7		Viscosity	1.94210E-05	Pars	@Tref
8		Internal Degree of Freedom	2		IDF = Int(2*Cp/R-5)
9					
10	Reference Values	Pressure	1.000E+00	Pa	
11		Temperature	322.031	K	
12					
13	Initial Conditions	Pressure	1.000E+00	Pa	
14		Temperature	322.031	K	
15		# of Super Particles per Cell	50		
16					
17	Walls	# of Walls	3		Max = 9
18			535		
19	Upstream BCs	Wall #	8		
20		Туре	1		1-Pressure, 2-Velocity
21		Pressure	1.000E+00	Pa	
22		Velocity	0.000	m/s	
23					
24	Downstream BCs	Wall #	9		
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26		Pressure	1.000E-01	Pa	< Upstream Pressure
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![](_page_7_Picture_5.jpeg)

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# **Example Flow Fields**

- $\Delta T$  and  $\Delta p$  across vane are produced.
- $\Delta T$  induces thermal creep flow.
- $\Delta p$  acts as area force to push vanes from black side.

![](_page_8_Figure_4.jpeg)

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# $\alpha_{\rm B} > \alpha_{\rm S}$ produces Torque

- Torque by  $\Delta p$  increases with decreasing  $\alpha_s$  for  $\alpha_s > 0.1$ ,
- then saturates for  $\alpha_{\rm S} < 0.1$ .

![](_page_9_Figure_3.jpeg)

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### **Rotation Speed of Vanes**

- Estimated by assuming torque of stationary vanes is the same as freely rotating vanes.
- Should be valid only at early state of starting rotation. [8]
- Time scale is sec-order as commonly observed.

![](_page_10_Figure_4.jpeg)

![](_page_10_Picture_5.jpeg)

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# What if Glass Bulb is Heated Up? $(T_G = T_V)$

- Flow fields are uniform  $(\Delta T \rightarrow 0, \Delta p \rightarrow 0)$  even for  $\alpha_{\rm B} \gg \alpha_{\rm S}$ .
- Apparent thermal creep flow is not induced.
- Revolution of vanes will stop.

![](_page_11_Figure_4.jpeg)

![](_page_11_Picture_5.jpeg)

# Summary

• New hypothesis

"Vane is isothermal, and  $\alpha_{\rm B} > \alpha_{\rm S}$ " has been proposed and investigated using heat transfer and DSMC simulations.

- The results have proved
  - vane is isothermal under sunlight, and
  - contrast of  $\alpha_{\rm B}$  and  $\alpha_{\rm S}$  can be an origin of  $\Delta T$  and  $\Delta p$  across vane.
  - $-\Delta p$  works as an area force to push vanes.
- Also found glass bulb temperature strongly affects revolution of vanes.

![](_page_12_Picture_8.jpeg)

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![](_page_13_Picture_20.jpeg)