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 ΔT
 - area force by Δp
- 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 α 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 $Bi \ll 1$ •

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

| | ρ (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.



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- 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 $(1 \alpha_{\rm S})$





Model Setup in DSMC_2D.xls

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

| □ ← ファイル | D • ♂ • ホーム | ▼ D5 挿入 | SMC_2D.xls [ページ レイアウト | 互換モード] 数式 | kz ej データ 校閲 | 雨 | _ □ | × A 共有 | | | | |
|--------------------------|----------------|---------------------------------------|---|---|---|---|-----------------------|-------------|----|-------------|----------|------------|
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| 4 4 1 | | | | | | 1 | | | 6 | Gas Prope | erties | Molecular |
| s 2 5 3 | | | 11110000 | | | 1111 | | | 7 | | | Viscosity |
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| 10 7 | 1 | 10000 | | | | 0000000 | 0011 | | 10 | Reference | e Values | Pressure |
| 11 8 12 9 | 1 0 | , , , , , , , , , , , , , , , , , , , | , , , , , , , , , , , , , , , , , , , | 0 0 0 0 0 0 0 0 0 | ~ 0000000000000 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 | 0 0 0 1 0 0 0 0 1 | | 11 | | | I emperat |
| 13 1 0 | 100 | | | A 0 3 2 0 | | | 0 0 0 0 0 1 | | 13 | Initial Con | ditions | Pressure |
| 14 1 | 1 1 0 0 0 | | | | , | 0 0 0 0 0 0 0 | 0 0 0 0 0 1 1 | 1 | 14 | Initial Con | Iditiono | Temperat |
| 15 3 | 10000 | | | | | 0 0 0 0 0 0 | 0 0 0 0 0 0 0 | 1 | 15 | | | # of Supe |
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| 38 5 1 | 0 0 0 0 0 | | | 0 0 0 0 2 3 0 | | | | 0 1 | 1 | | 1 | 0 |
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| 1 | A | В | С | D | E |
|----|--------------------|-------------------------------|-------------|---------|--|
| 1 | | | Value | Unit | Note |
| 2 | | | | | |
| 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 | | |
| 25 | | lype | 1 | | 1-Pressure, 2-Reflection Probability, 3-Perfect Vacuum |
| 26 | | Pressure | 1.000E-01 | Pa | < Upstream Pressure |
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| 2 | 348.000 | 1.000 | | | 1.000 | | | | |
| 3 | 348.000 | 0.010 | 0.990 | | 1.000 | | | | |
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Example Flow Fields

- ΔT and Δp across vane are produced.
- ΔT induces thermal creep flow.
- Δp acts as area force to push vanes from black side.



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

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



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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.





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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.





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 ΔT and Δp across vane.
 - $-\Delta p$ works as an area force to push vanes.
- Also found glass bulb temperature strongly affects revolution of vanes.



References

- [1] P. Gibbs, math.ucr.edu/home/baez/physics/General/LightMill/light-mill.html, 1996.
- [2] S. R. Wilk, Optics & Photonics News, 2007, pp. 17-19.
- [3] M. Ota, T. Nakano, and M Sakamoto, Trans. Japan Soc. Mech. Engineers, B, 65 (1999), pp. 2016-2022.
- [4] M. Ota, T. Nakano, and M Sakamoto, Math. and Comput. Sim., 55 (2001), pp. 223-230.
- [5] M. Nadler, Diploma Thesis, Institute for Astronomy and Astrophysics, 2008.
- [6] L-H, Han, S. Wu, J. C. Condit, N. J. Kemp, T. E. Milner, M. D. Feldman, and S. Chen, Appl. Phys. Lett., 96 (2010), 213509.
- [7] S. Taguchi and K. Aoki, J. Fluid Mech.,694 (2012), pp. 191-224.
- [8] S. Chen,K. Xu, and C. Lee, Phys. Fluids 24 (2012), 111701.
- [9] G. Dechriste and L. Mieussens, 2015. <hal-01131756>.
- [10] D. Wolfe, A. Larraza, and A. Garcia, Phys. Fluids, 28 (2016), 037103.
- [11] SENSBEY, "各種物質の熱的性質", www.sensbey.co.jp/pdffile/materialpropety.pdf
- [12] K. Hisahara, Dr. Thesis, Gumma Univ., 2014.
- [13] チノー, "放射率表", www.chino.co.jp/support/technique/thermometers/housyaritsu.html.
- [14] 堀場製作所, "放射温度計のすべて", (2008),
 - www.horiba.com/fileadmin/uploads/Process-Environmental/Documents/thermometry.pdf.
- [15] TECHNO, "熱流束値の目安", www.techno-office.com/file/heatflux-estimate.pdf.
- [16] 圓山, "第8章伝熱問題のモデル化と設計", (2014),
 - www.ifs.tohoku.ac.jp/maru/sub/lecture/hachi2014/data/2014.10/chapter08.pdf.
- [17] www2b.biglobe.ne.jp/~denpoh/Software/DSMC_xls/

