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

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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.

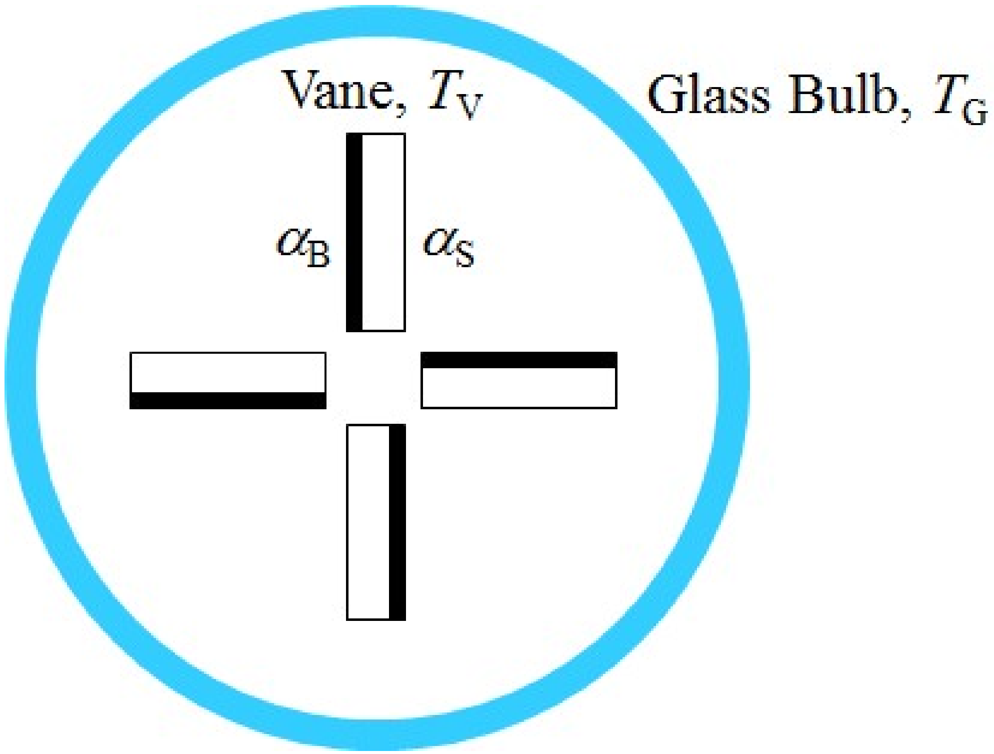
Past Simulation Studies [3-10]

- 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, $T_B > T_S$.
  - accommodation coefficient α is uniform and same at both sides of vane.

New Hypothesis proposed in This Study

- Vanes is **isothermal at T_V**.
- Accommodation coefficient α_B at black side of vane is different from that at shiny side α_S, and $\alpha_B > \alpha_S$.



Estimating Vane Temperature

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

$$\begin{cases} q_{\mathrm{in}} - \left(q_{\mathrm{g,B}}^{t} + q_{\mathrm{r,B}}^{t}\right) = -\kappa \dfrac{\partial T_{\mathrm{V}}^{t}}{\partial x} \\ \rho L_{\mathrm{b}} C_{\mathrm{p}} \dfrac{\partial T_{\mathrm{V}}^{t+\Delta t}}{\partial t} = q_{\mathrm{in}} - \left(q_{\mathrm{g,B}}^{t} + q_{\mathrm{r,B}}^{t}\right) - \left(q_{\mathrm{g,S}}^{t} + q_{\mathrm{r,S}}^{t}\right) \end{cases}$$

$$q_{\mathrm{g,B/S}}^{t} = \frac{1}{4} n \bar{v} \Delta E = \frac{1}{2} nk \sqrt{\frac{8kT_{\mathrm{g}}}{\pi m}} \left(T_{\mathrm{V,B/S}}^{t} - T_{\mathrm{g}}\right)$$

$$q_{\mathrm{r,B/S}}^{t} = \varepsilon_{\mathrm{B/S}} \sigma \left\{ \left(T_{\mathrm{V,B/S}}^{t}\right)^{4} - T_{\mathrm{g}}^{4} \right\}$$

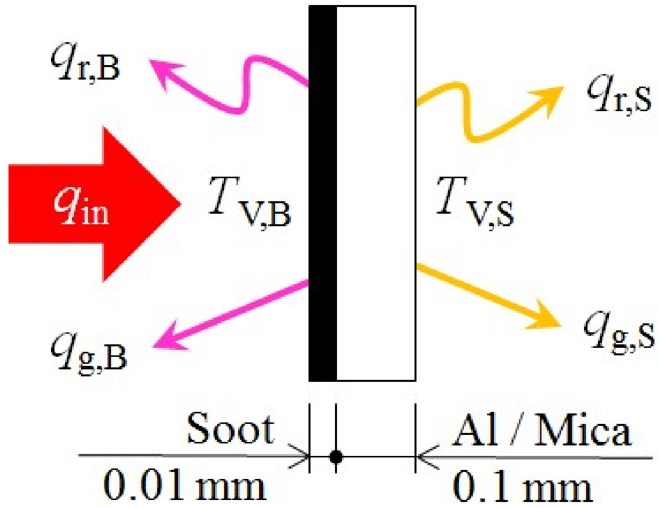
Ambient

Air, 1 Pa

T_{g}=298 K

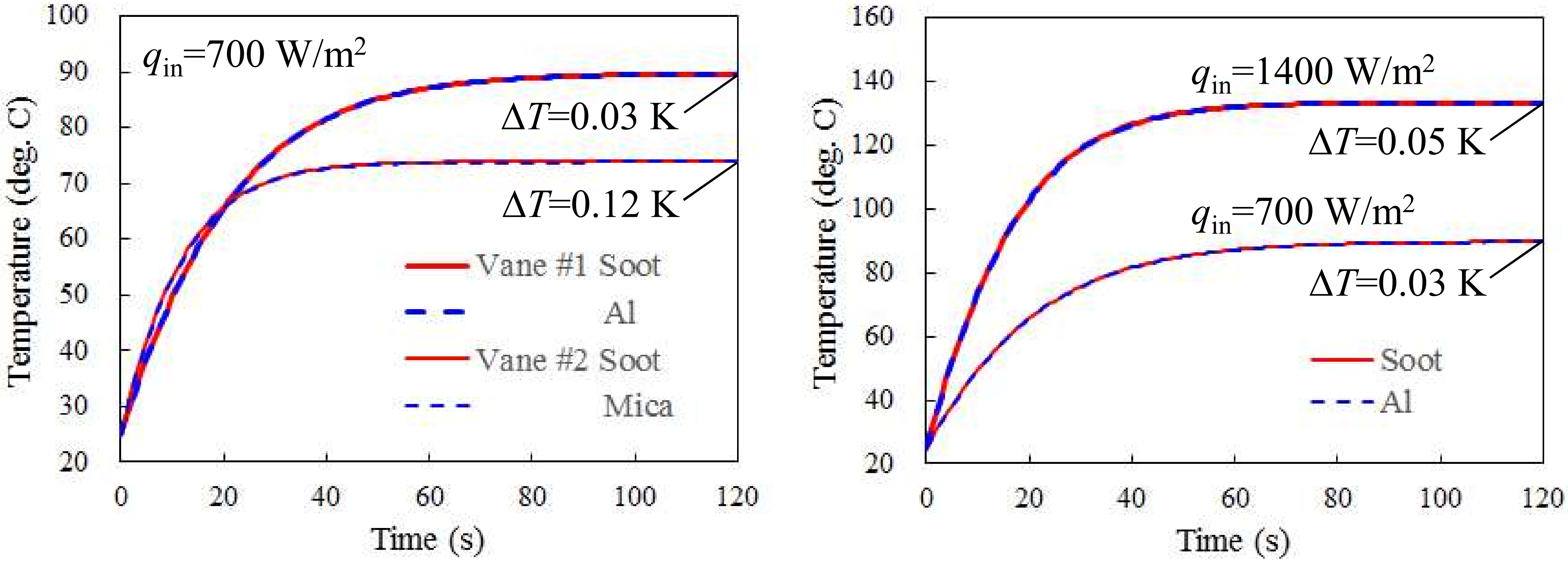
Material Properties [11-14]

	ρ (kg/m^3)	C_{p} (J/kg-K)	κ (W/m-K)	ε
Al	2688	905	237	0.17
Mica	2100	880	0.5	0.72
Soot	100	1000	0.05	0.95



Estimating Vane Temperature (cont'd)

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

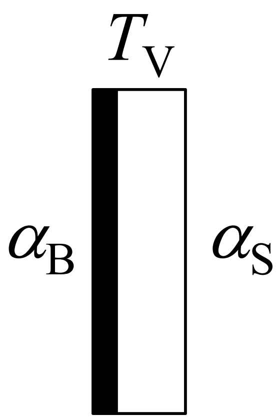


DSMC_2D.xls [17]

- Multipurpose 2D DSMC software created on MS-Excel
  - www2b.biglobe.ne.jp/~denpoh/Software/DSMC_xls/

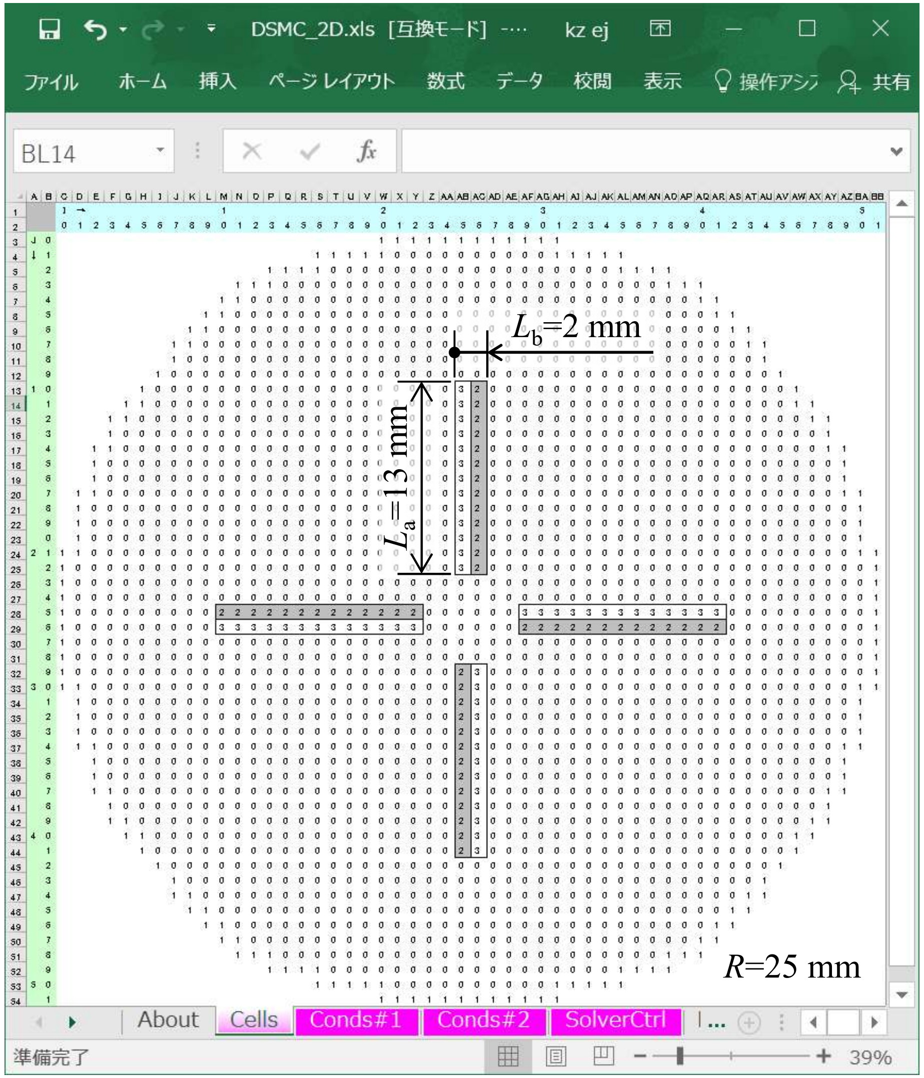
- Gas (Air)
  - Diatomic molecule with rotational degrees of freedom
  - Molecular model: Maxwell molecule
  - Collision models: VHS model, Larsen-Borgnakke model

- Accommodation coefficients
  - Black side: $\alpha_B = 1$ (diffuse reflection)
  - Shiny side: diffuse reflection α_S + specular reflection $(1 - \alpha_S)$



Model Setup in DSMC_2D.xls

- Vane length L_a = 13 mm, thickness L_b = 2 mm



	A	B	C	D	E
1			Value	Unit	Note
2					
3	Cells	dx	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	Pa・s	@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					
19	Upstream BCs	Wall #	8		
20		Type	1		1-Pressure, 2-Velocity
21		Pressure	1.000E+00	Pa	
22		Velocity	0.000	m/s	
23					
24	Downstream BCs	Wall #	9		
25		Type	1		1-Pressure, 2-Reflection Probability, 3-Perfect Vacuum
26		Pressure	1.000E-01	Pa	< Upstream Pressure

About Cells Conds#1 Conds#2 SolverCtrl Log n V p T Ttr Tint q Pl...

準備完了 100%

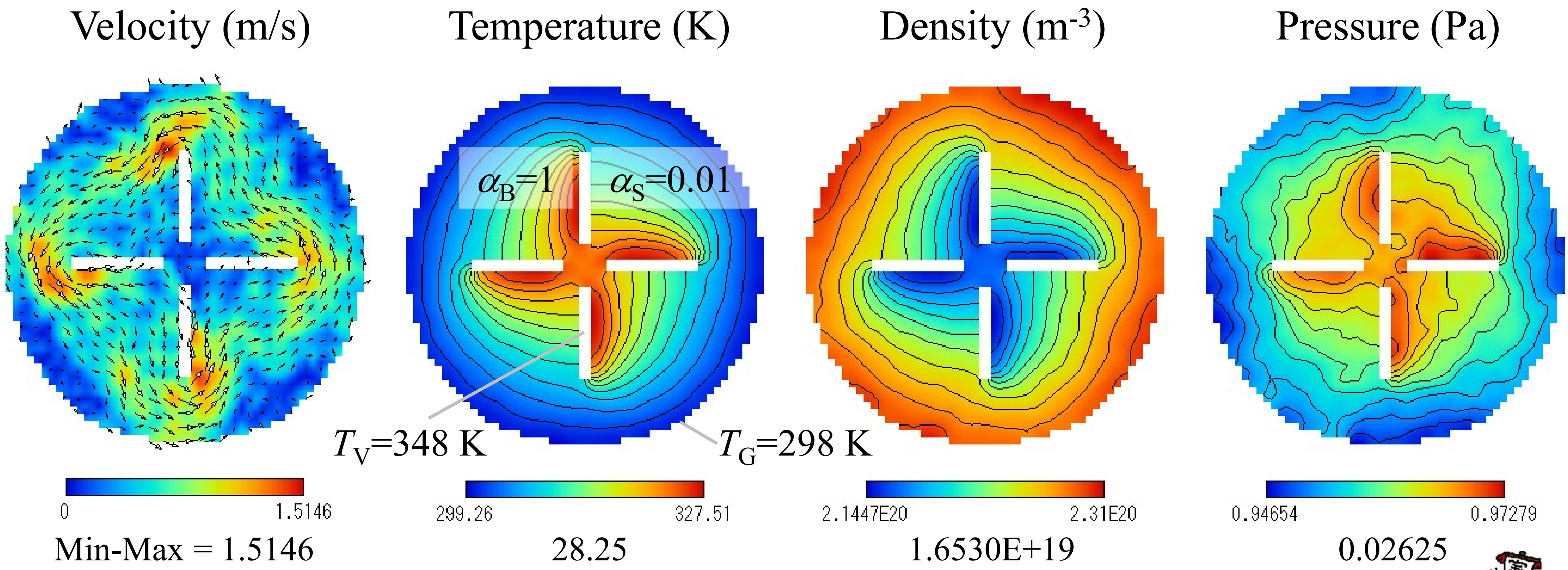
Wall #	Temperature (K)	Probability: Diffuse Reflection	Specular Reflection	Sticking	TOTAL	CHECK
1	298.000	1.000			1.000	
2	348.000	1.000			1.000	
3	348.000	0.010	0.990		1.000	
4						
5						
6						
7						
8						
9						

About Cells Conds#1 Conds#2 SolverCtrl Lo...

準備完了 100%

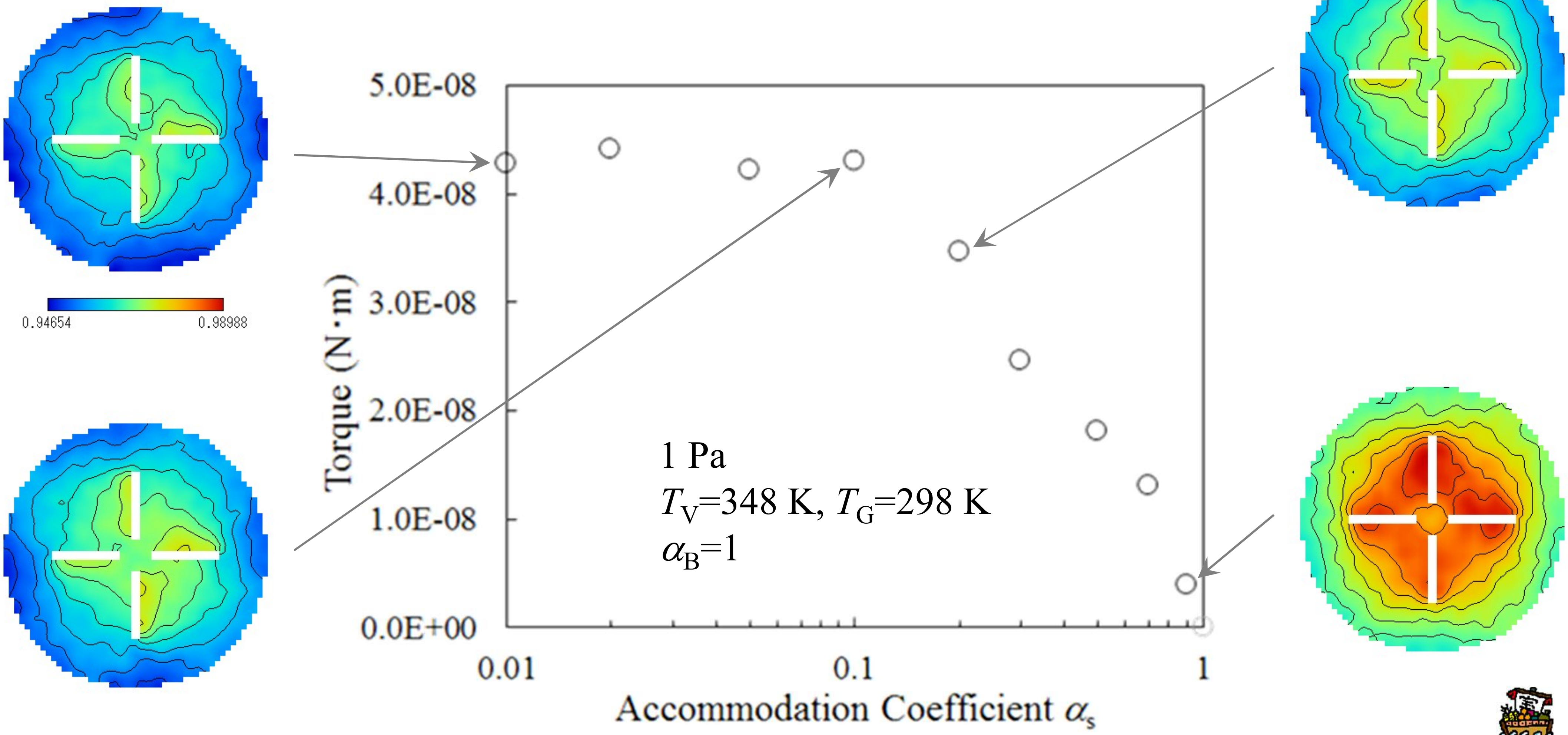
Example Flow Fields

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



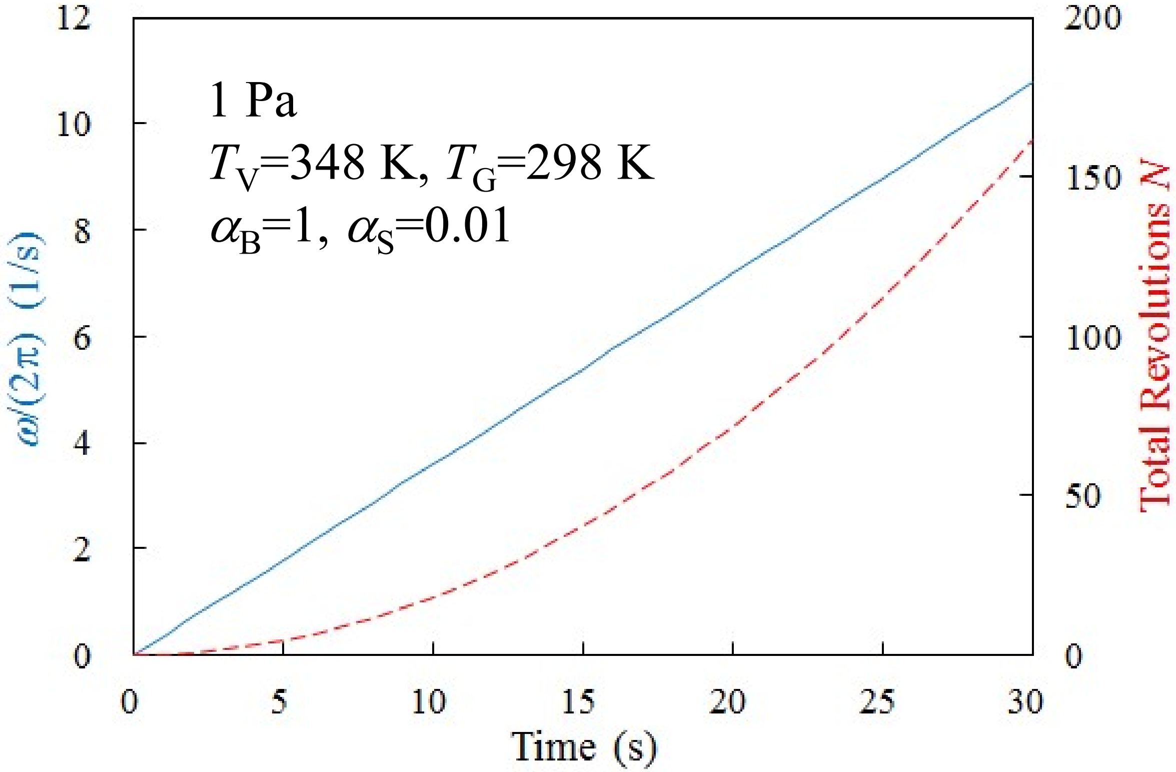
$\alpha_B > \alpha_S$ produces Torque

- Torque by Δp increases with decreasing α_S for $\alpha_S > 0.1$,
- then saturates for $\alpha_S < 0.1$.



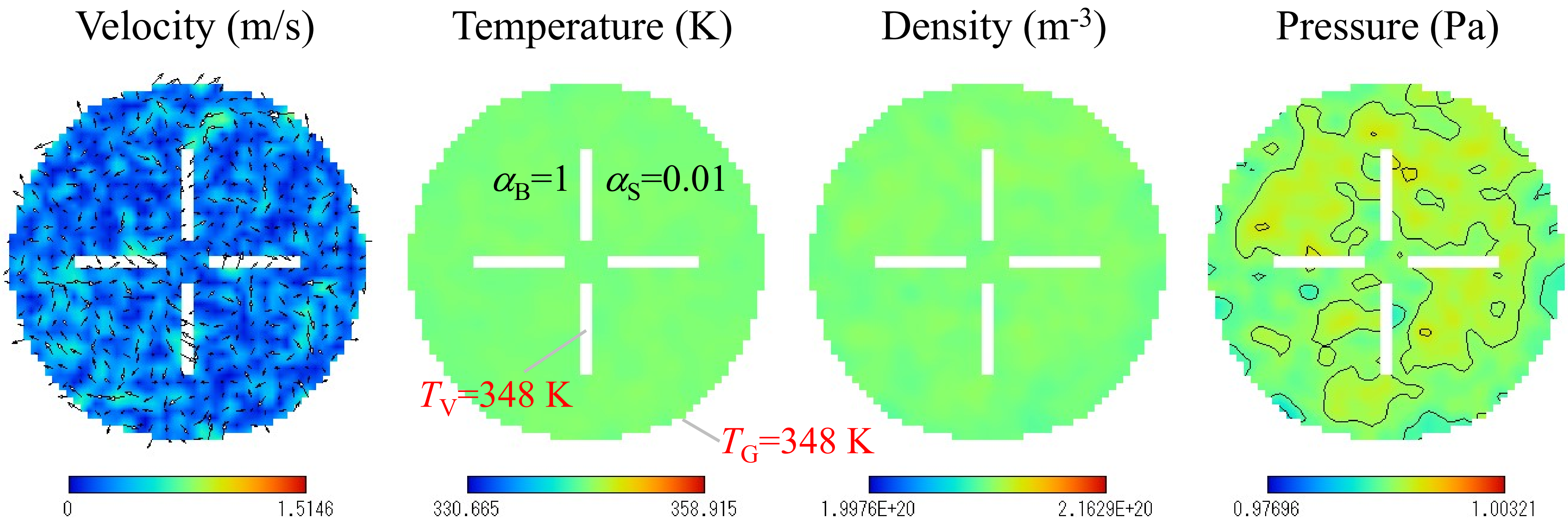
Rotation Speed of Vanes

- 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.



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

- Flow fields are uniform (ΔT –> 0, Δp –> 0) even for $\alpha_B \gg \alpha_S$.
- Apparent thermal creep flow is not induced.
- Revolution of vanes will stop.



Summary

- New hypothesis

  "Vane is isothermal, and $\alpha_B > \alpha_S$"

  has been proposed and investigated using heat transfer and DSMC simulations.

- The results have proved
  - vane is isothermal under sunlight, and
  - contrast of α_B and α_S can be an origin of ΔT and Δp across vane.
  - Δp works as an area force to push vanes.

- Also found glass bulb temperature strongly affects revolution of vanes.

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