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Radiative Transfer by Nano-Structure for Environmental Issues - Development of Cool Black -

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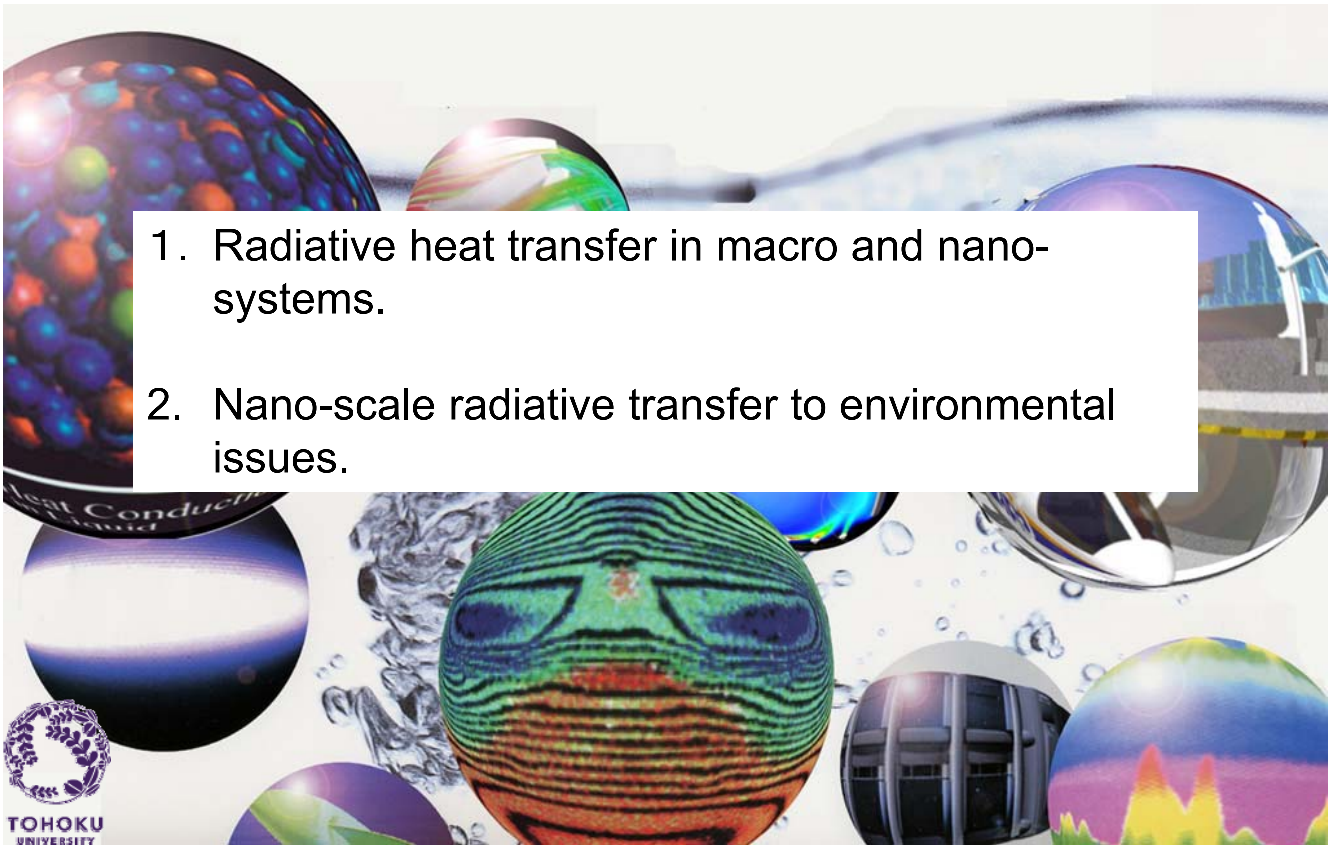
Outline



1. Radiative heat transfer in macro and nano-systems.
2. Nano-scale radiative transfer to environmental issues.

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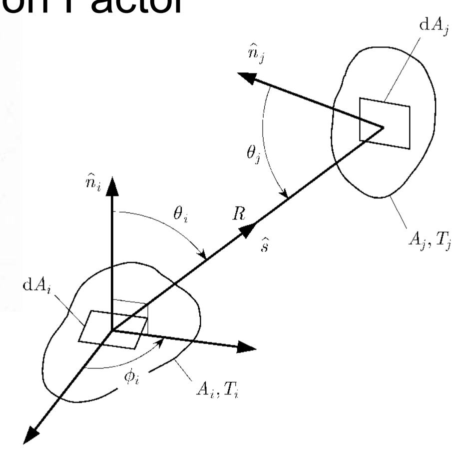
Radiative Heat Transfer in Macro and Nano System

Radiative Heat Transfer in Macro Scale System

Configuration Factor

$$F_{di,j} \equiv \frac{\int_0^\infty \int_{2\pi} \delta_i^j(\hat{s}) I_\lambda(\lambda, \hat{s}, T_i) \cos\theta_i \, \mathrm{d}\Omega \, \mathrm{d}\lambda}{\int_0^\infty \int_{2\pi} I_\lambda(\lambda, \hat{s}, T_i) \cos\theta_i \, \mathrm{d}\Omega \, \mathrm{d}\lambda}$$

$$= \frac{\int_0^\infty \int_{2\pi} \delta_i^j(\hat{s}) \, \varepsilon_{\theta,\lambda}(\lambda, \hat{s}, T_i) \, I_{b,\lambda}(\lambda, T_i) \cos\theta_i \, \mathrm{d}\Omega \, \mathrm{d}\lambda}{\int_0^\infty \int_{2\pi} \varepsilon_{\theta,\lambda}(\lambda, \hat{s}, T_i) \, I_{b,\lambda}(\lambda, T_i) \cos\theta_i \, \mathrm{d}\Omega \, \mathrm{d}\lambda}$$



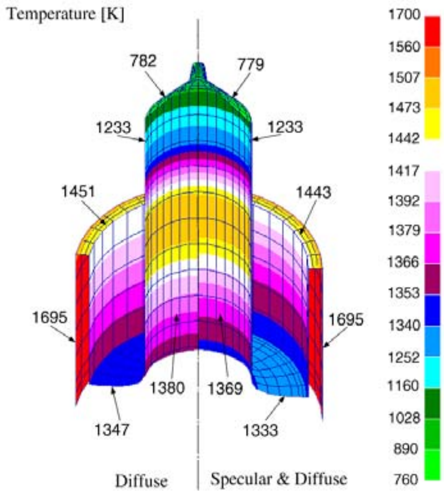
$$F_{i,j} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi R^2} \, \mathrm{d}A_j \, \mathrm{d}A_i$$

Configuration Factor $F_{i,j}$

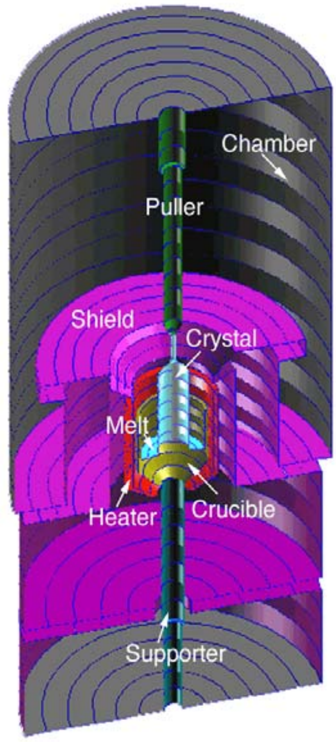
$$\equiv \frac{\text{Energy leaving the surface } i \text{ and intersepted by surface } j}{\text{Total energy leaving the surface } i}$$

Configuration Factors of Arbitrary Configuration

Radiative Heat Transfer with Specular Surfaces of CZ Furnace

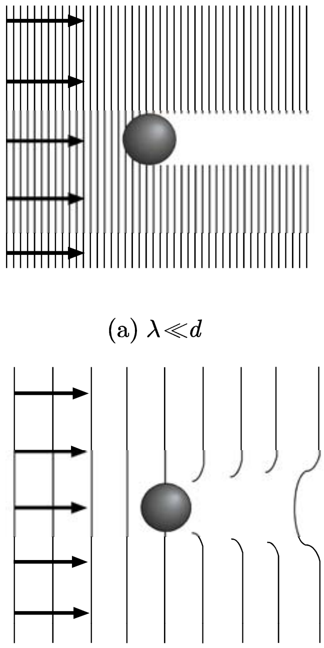


Temperature Distribution in CZ Furnace



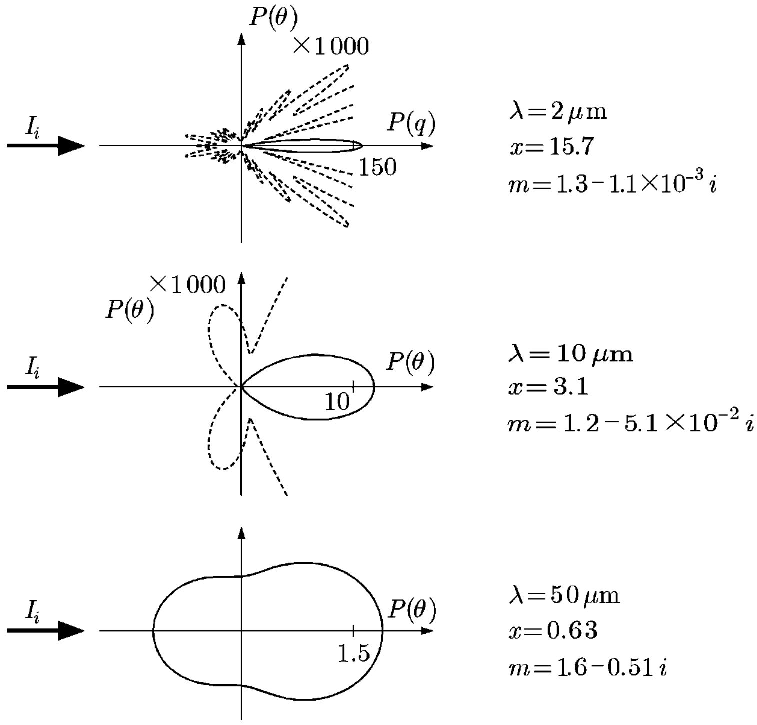
Guo & Maruyama et al. J. Crystal Growth (1998)

Scattering of Water Droplet



(a) $\lambda \ll d$

(b) $\lambda \cong d$



Phase function of water droplet of diameter 10μm against various wavelength

Maruyama, Light Energy Engineering, 2004

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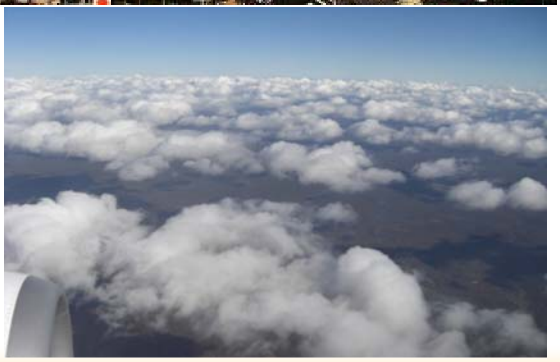
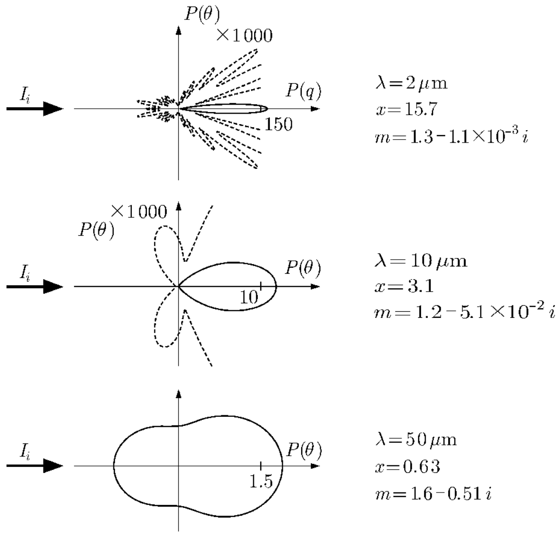
Light scattering by particles comparable size with the light wavelength



Mie Scattering



Light scattering of a water particle of diameter10μm irradiated by various wavelength lights

Maruyama, Light Energy Engineering, 2004

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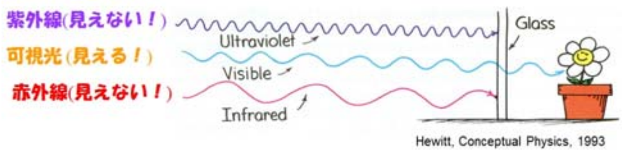
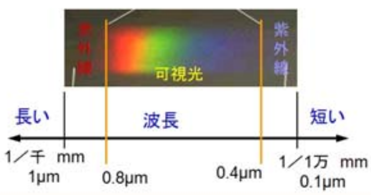
Visible and Invisible Lights

Visible or Invisible?

http://www.ifs.tohoku.ac.jp/ifs_movie/jpn/ifs_channel/movie_03_b.html



髪の毛： 100μm



Global Warming and Radiative Heat Transfer

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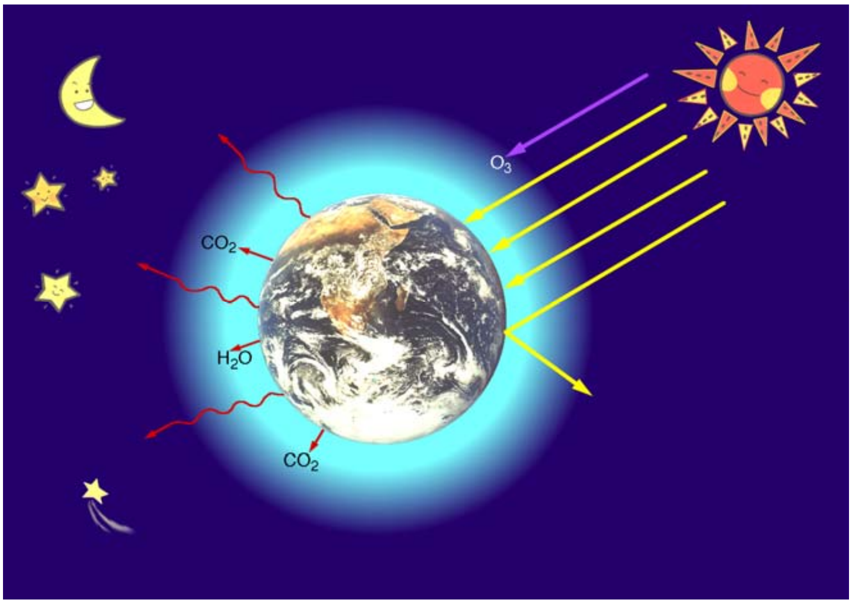

Global temperature is determined by the heat balance of the energy irradiated (wavelength =$0.5\ \mu m$) by the sun and thermal emission (wavelength= $10\ \mu m$) form the earth.
The greenhouse gases are transparent against the sunlight, however, they absorb the long infrared from the earth. The gases increase the temperature of the earth.

Changing Energy Balance of the Earth

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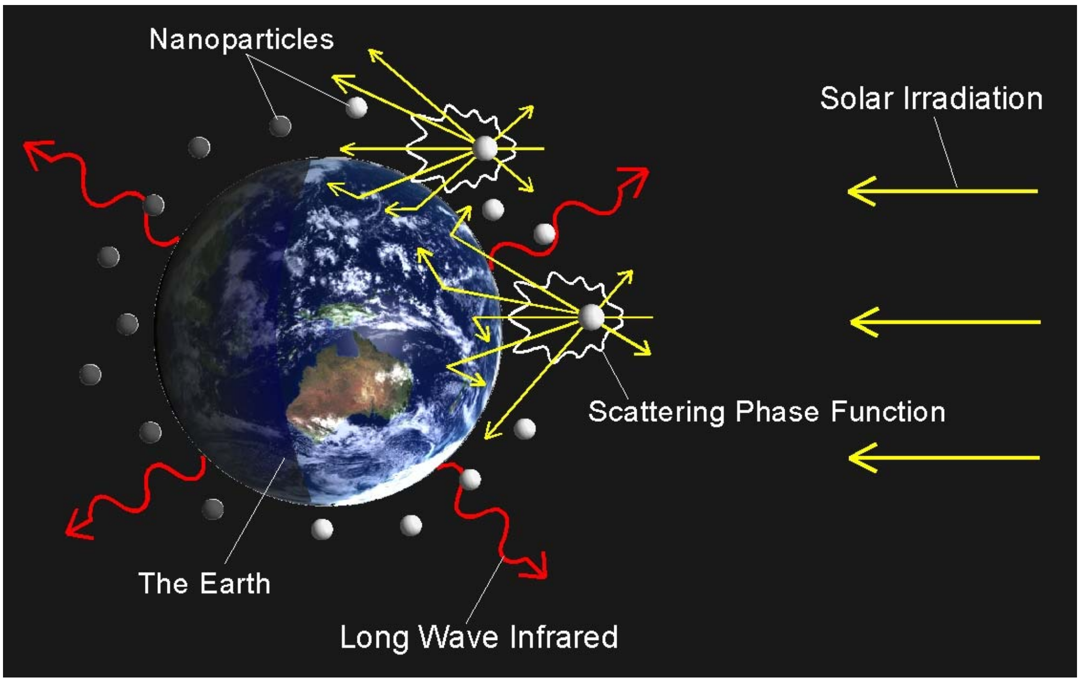

Sunlight scattered by particle in the atmosphere.

Heat Transfer Control by Dispersing Nano-particles

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Cooling of the Earth by Nano-particles

Proposal

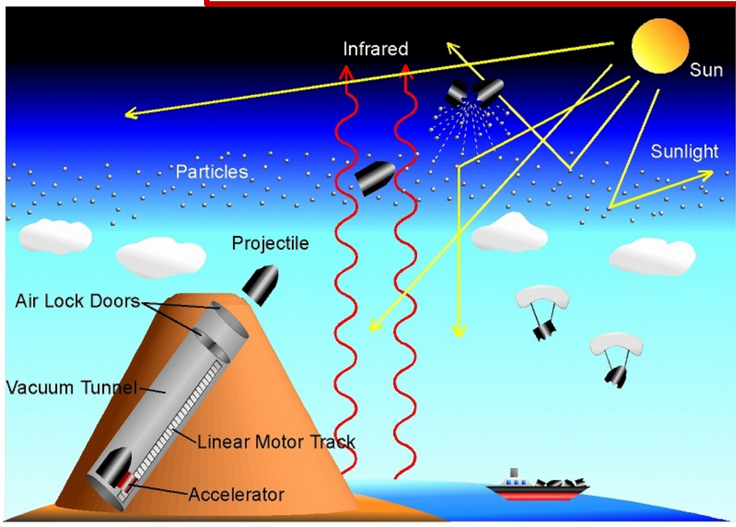
Optical Characteristics of Nano-particles

↓

Controlling Solar Irradiation by Dispersing Nano-Particles in Stratosphere

↓

Decreasing Temperature



- Material : **Al_2O_3**
- Altitude : **30 km**
- Launching Site : **4000 m**
- Acceleration : **Linear Motor**
- Projectile : **10 tons**

Maruyama et al., JSME J. Thermal Science and Technology (2015)

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Difference between Micro and Nano Systems

Macro and nano-systems can be defined in terms of radiative transfer

Macro-system :

The size of the system element is much larger than the wavelength of radiation. The radiation can be treated as energy rays and geometrical optics can be applied.

Nano-system :

The size of the system element is similar or smaller than the wavelength of radiation. Wave and quantum characteristics appear in the radiative transport.

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Nano-scale Radiative Transfer to Solve Environmental Issues

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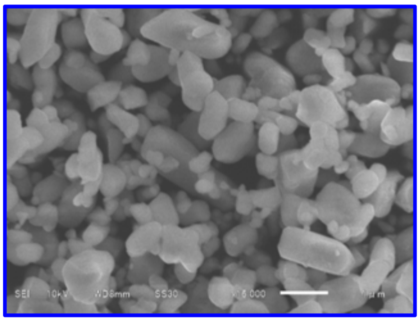
Controlling Environment by Nano-technology

Phenomenon in nano scale



Pigment particle observed by Scanning Electron Microscope (SEM)

Nanotechnology

Spectral reflectance control

Absorption

Refraction

The amount and direction of scattering energy

Saving energy for air conditioning

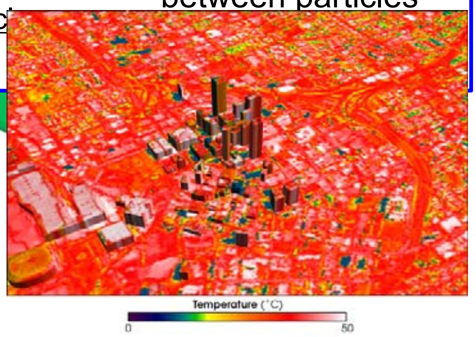
http://sansyouzi.noblog.jp/e22.html

Environmental problem

Phenomenon in macro scale

- The clearance between particles

Urban heat island



Collect thermal data on metropolitan Atlanta, Georgia
Daytime air temperatures of only about 26.7 degrees
Wikipedia

Control of the phenomenon in nano scale has the big impact on the phenomenon in macro scale.

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Energy Saving by Nano-particles

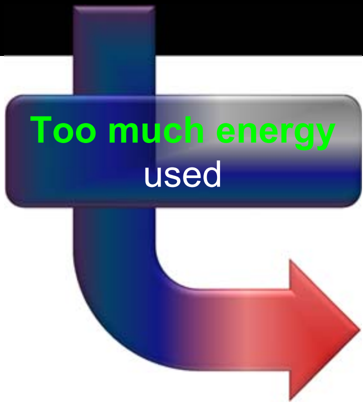
http://image4.kurumaerabi.com/

Advantage

Dark colors are used to paint the buildings or cars to improve **aesthetic** performance

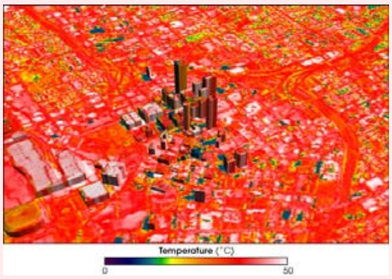
Disadvantage

- ✓ **High absorption** against sunlight
- ✓ Increasing **indoor temperature**
- ✓ Increasing **cooling load** demand



Environmental problem

Urban heat island



Collect thermal data on metropolitan Atlanta, Georgia
Daytime air temperatures of only about 26.7 degrees
Wikipedia

Global warming

Polar bear struggling to survive on the small ice left due to global warming
http://s92zfrt.edu.glogster.com/climate-change-polar-bears-by-jessica-gaalema/

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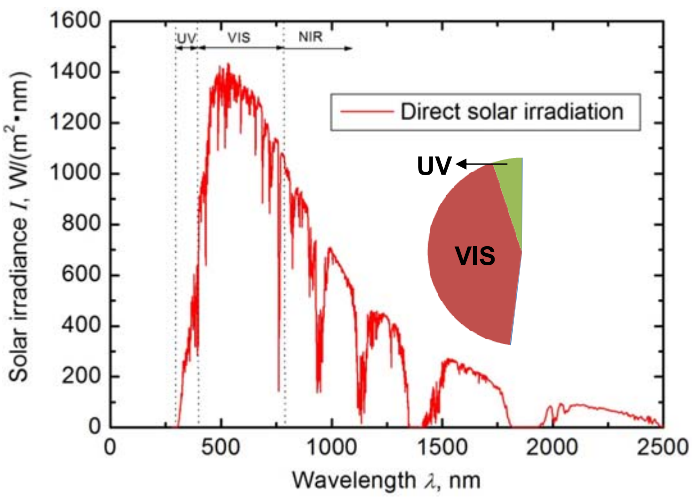
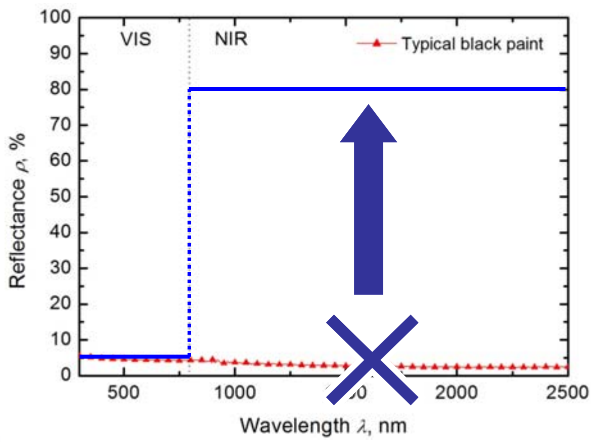
Energy saving by nano-particles

Contribution of UV/VIS/NIR lights in solar energy



Spectral solar irradiations



Reflectance of typical black paint

- 52% of near-infrared (NIR) light : 0.78–2.5μm → **Most effective to heat**
- 43% of visible (VIS) light : 0.38–0.78μm
- 5% of ultraviolet (UV) light : 0.30–0.38μm

http://ja.wikipedia.org/wiki

It is possible to reduce sunlight absorption of exteriors by reflecting NIR energy.

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Numerical analysis

The RTE is solved to find spectral reflectance of the coating system

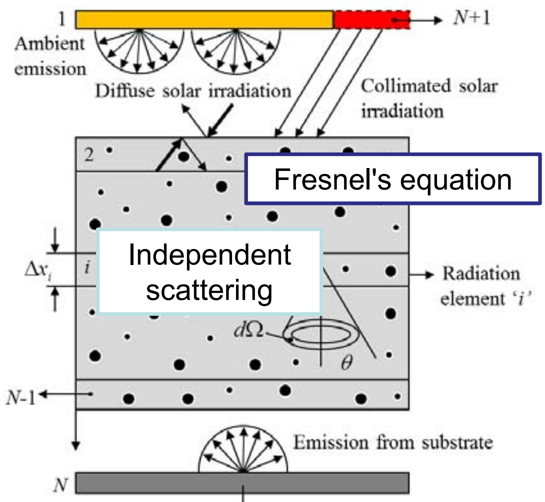
Radiative Transfer Equation

$$\frac{dI_\lambda(x,\mu)}{dS} = \beta\left[-I_\lambda(x,\mu) + (1-\omega)I_{b,\lambda}(T) + \frac{\omega}{2}\int_{-1}^{1} I_\lambda(x,\mu')\Phi_\lambda(\mu')\,d\mu'\right]$$

Reduced term by scattering and absorption | Emission term | Amplification term by scattering

Emission term
Theoretical design (VIS-NIR) : 0
Thermal analysis (VIS-IR) : Considered

Solar irradiation
Bird's model
Bird, R. E., Riordan, C., *Journal of Climate and Applied Meteorology*, Vol. 25, pp 87-97, 1986.



One-dimensional plane-parallel model

M. Baneshi, et al., *JQSRT*, 110, (2009), 192.
M. Baneshi, et al., *J Therm Sci Tech-JPN*, 4, (2009), 131.
M. Baneshi, et al., *JQSRT*, 112, (2011), 1197.

Radiation Element Method by Ray Emission Model (REM^2)

S. Maruyama, *Int. J. Heat Mass Tran*, 41, (1998), 2847.

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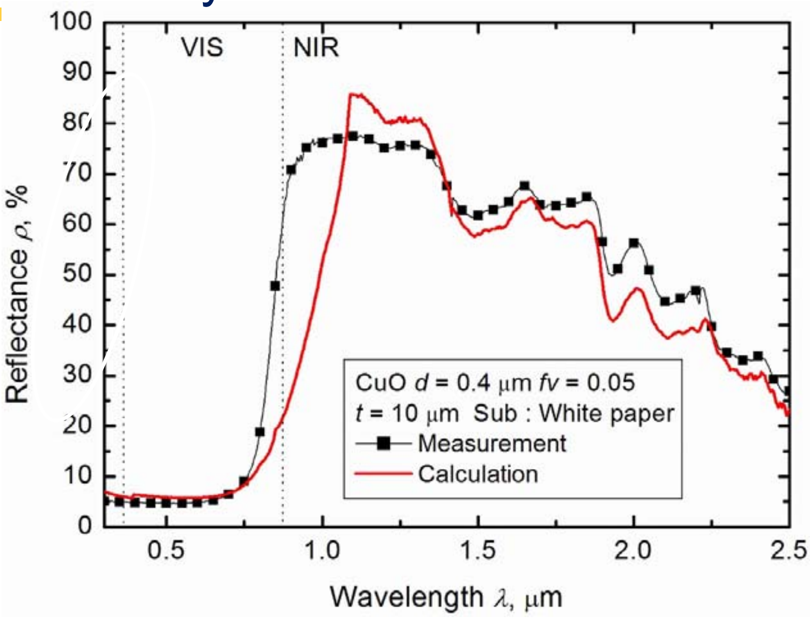
Comparison between measurement and analysis



Comparison between measured and calculated reflectivity of CuO coating on the white paper

The spectral behaviors of measured and calculated reflectance are almost same. → Evidence of our theoretical designing method

Gonome & Maruyama, et al., JQSRT, (2013)

Experiment

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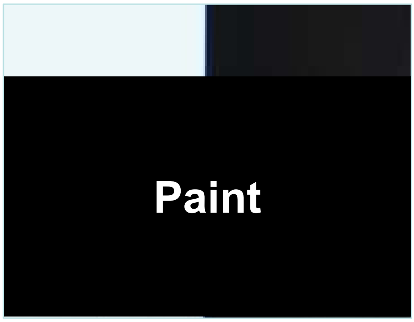
Specifications of the pigmented particles

Composition	Mean diameter of particles [μm]	Chemical company
CuO	0.050	Wako Pure Chemical Industries
CuO	0.89	Kojundo Chemical Laboratory
CuO	3.0	Wako Pure Chemical Industries

Preparing the coating

CuO powder

Mix with clear acrylic resin and paint



Standard black and white paper introduced by Japan Industrial Standards (JIS)

Gonome & Maruyama et al., JQSRT, 132, (2014).

Experiment

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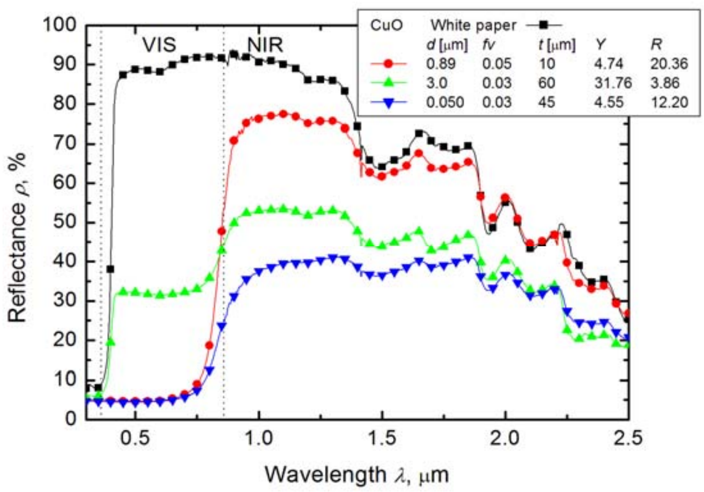
Particle size



Variation in the measured spectral reflectivity with particle diameter for CuO pigmented coating on white paper

Control of the particle size

Control of the spectral reflectance

Particle diameter *d* : 3.0 μm

Moderate VIS reflectance

Gray color

Hiding power of the big particle is low.

d : 0.89, 0.050 μm

Low VIS reflectance

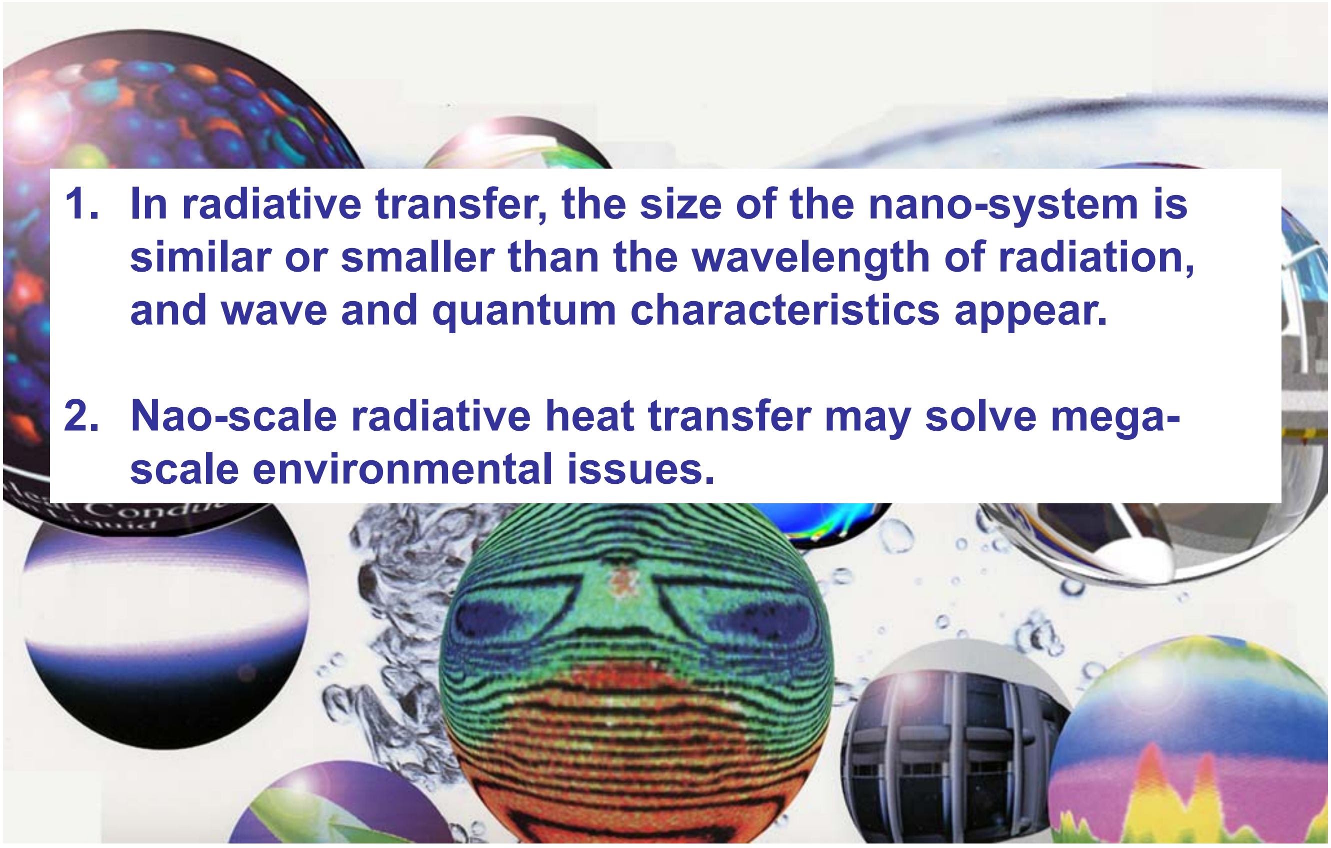
Black color

NIR reflectance

d : 0.89 μm > *d* : 0.050 μm

Gonome & Maruyama et al., JQSRT, 132, (2014).

Conclusions



1. In radiative transfer, the size of the nano-system is similar or smaller than the wavelength of radiation, and wave and quantum characteristics appear.

2. Nao-scale radiative heat transfer may solve mega-scale environmental issues.

TOHOKU

Radiative Transfer by Nano-Structure for Environmental Issues

Thank you for your attention

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