New Effects in Turbulent Aerosol Transports: Theory, Experiments and Observations

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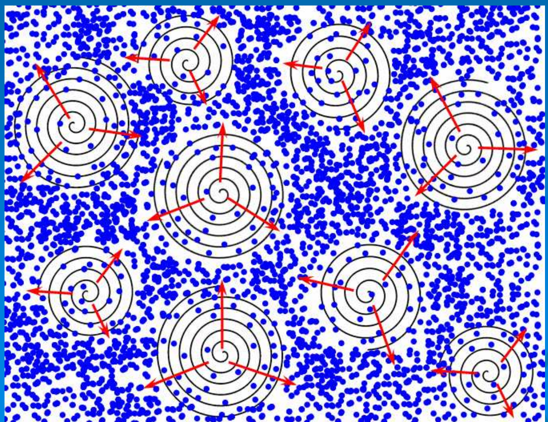

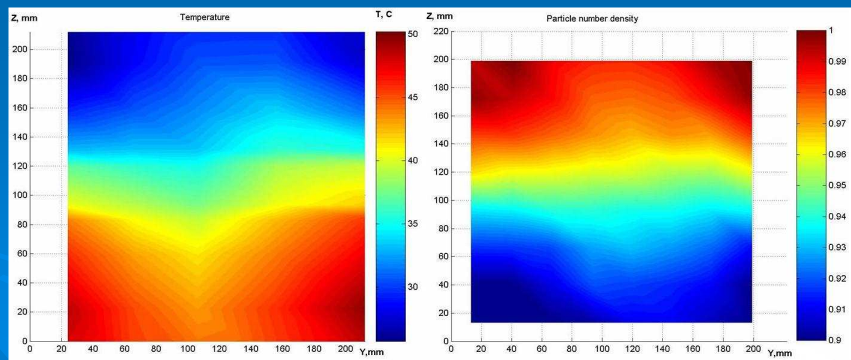

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Outline

- Introduction
- Formation of large-scale particle layers:
  - theory of the new phenomenon of turbulent thermal diffusion
  - experimental detection of turbulent thermal diffusion
  - meteorological and environmental applications
- Formation of small-scale particle clusters:
  - clustering instability
  - possibility for the experimental study of the small-scale clusters
  - meteorological and environmental applications
- Conclusions

Background

- Brownian diffusion – Einstein (1905);
  Smoluchowsky (1906)
- Thermophoresis – Tyndall (1870)
- Molecular thermal diffusion in gases – Enskog (1911); Chapman and Dootson (1917)
- Turbulent diffusion – Taylor (1921)

Brownian diffusion of small particles and gases

$$\frac{\partial n}{\partial t} = \mathrm{D}\,\Delta n$$

$$\mathrm{D} = \frac{\mathrm{k_B\,T}}{6\pi\,\rho\,\nu\,a_*}$$

n - number density of particles

D - coefficient of molecular diffusion

$$[n] \rightarrow \mathrm{cm}^{-3}$$

Molecular thermal diffusion in gases and thermophoresis of small particles

$$\frac{\partial n}{\partial t} = -\mathrm{div}\,\mathbf{J}_M$$

$$\mathbf{J}_M = -D\left(\nabla n + k_t \frac{\nabla T}{T}\right)$$ - flux of particles

D - coefficient of molecular diffusion

$k_t \propto n$ - thermal diffusion ratio

$D_M = Dk_t$ - coefficient of molecular thermal diffusion

$$[n] \to \mathrm{cm}^{-3}$$

Turbulent Diffusion

Taylor (1921)

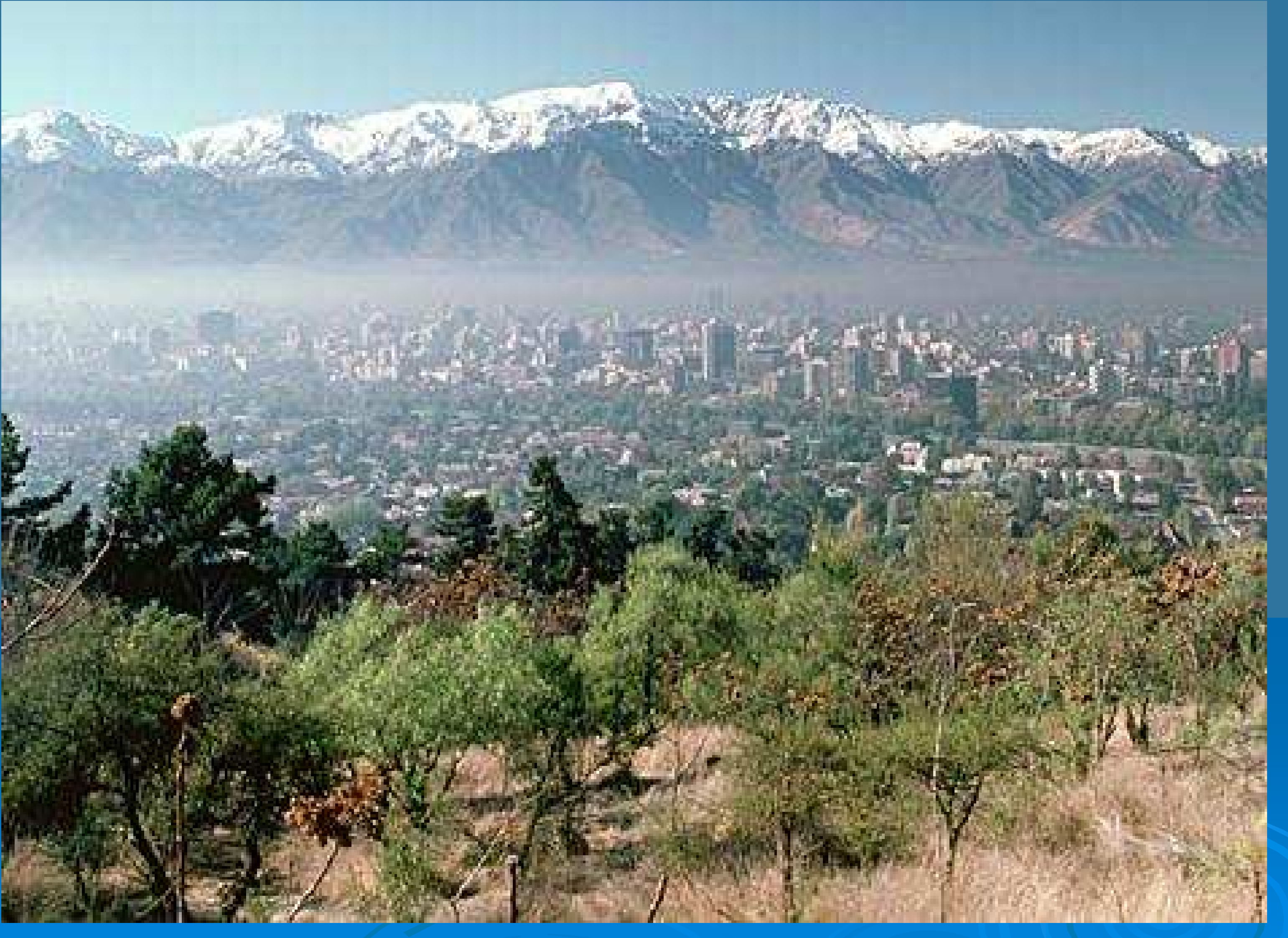
$$D_T \approx \frac{1}{3} L\, u >> D \qquad \frac{\partial\, \overline{N}}{\partial\, t} + \mathrm{div}(\overline{N}\ \overline{\mathbf{V}}) = D_T \Delta\, \overline{N}$$

- Turbulence results in a sharp increase of the diffusion coefficient (Taylor, 1921).

1921-1996

- Turbulence causes a decay of particle inhomogeneities.
- However, the opposite process, the preferential concentration of particles in turbulent flows is still poorly understood.

FORMATION OF AEROSOL LAYERS

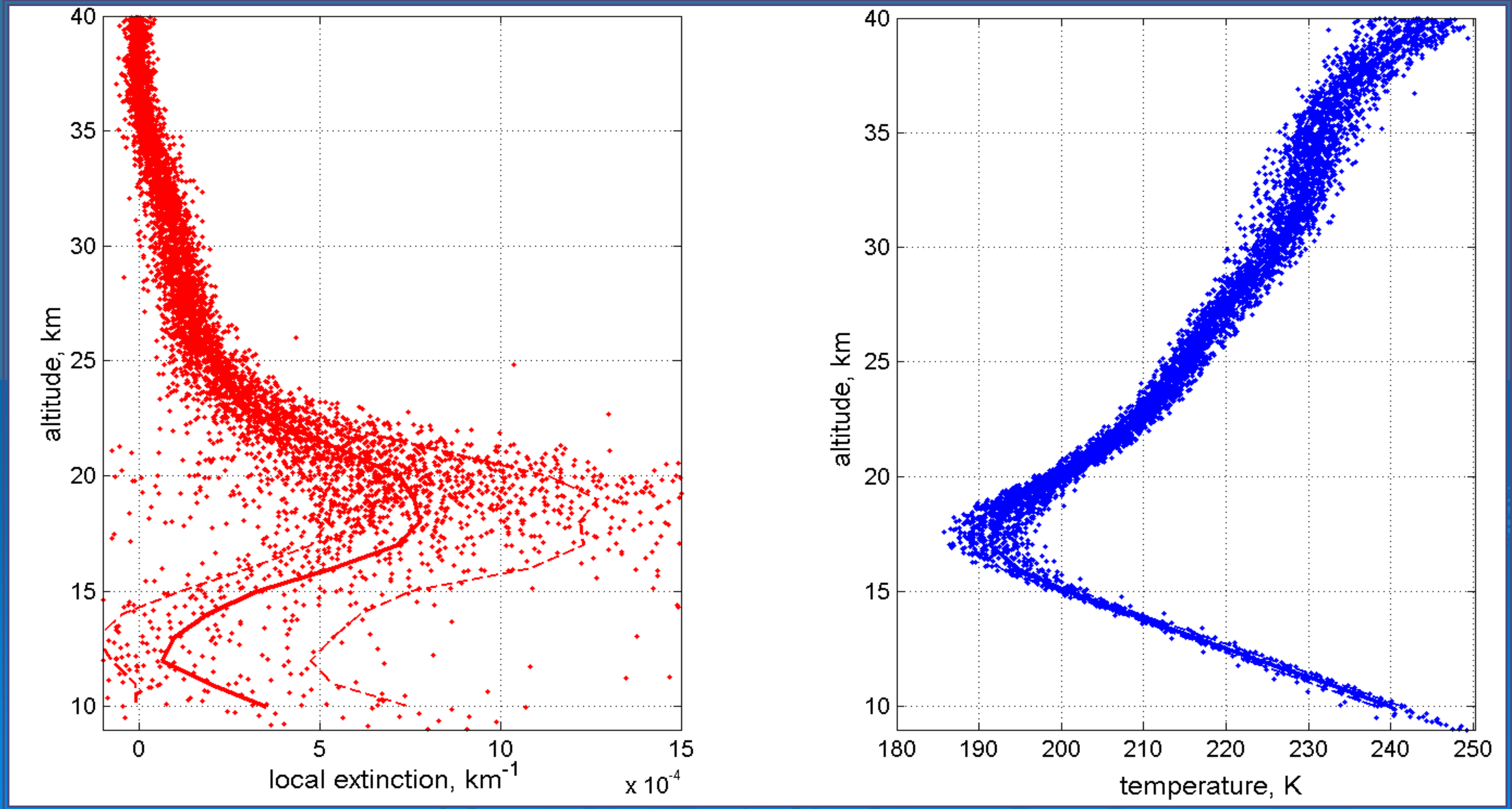


Smog cloud over Santiago

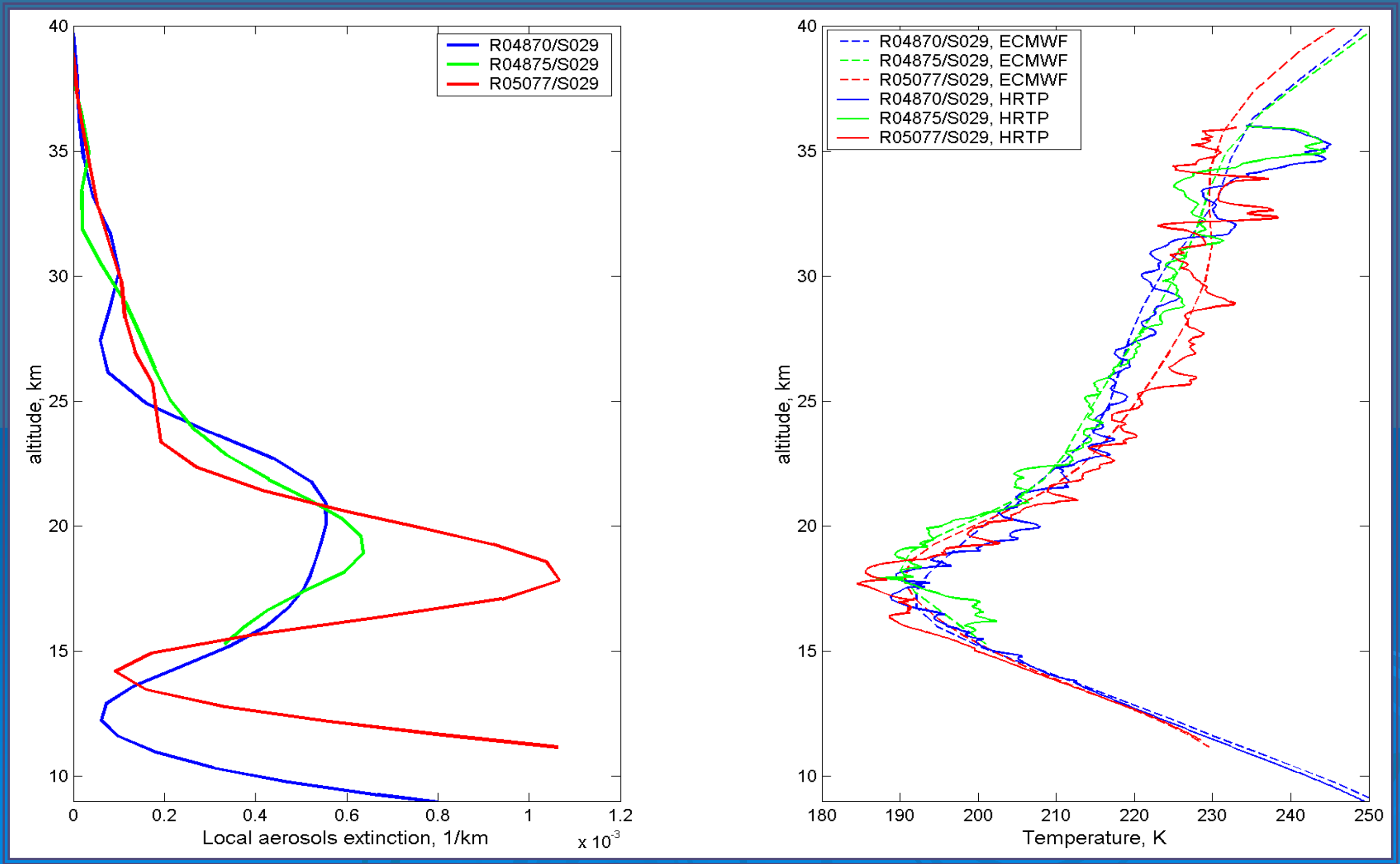
FORMATION OF AEROSOL LAYERS

Smog cloud over Los Angeles

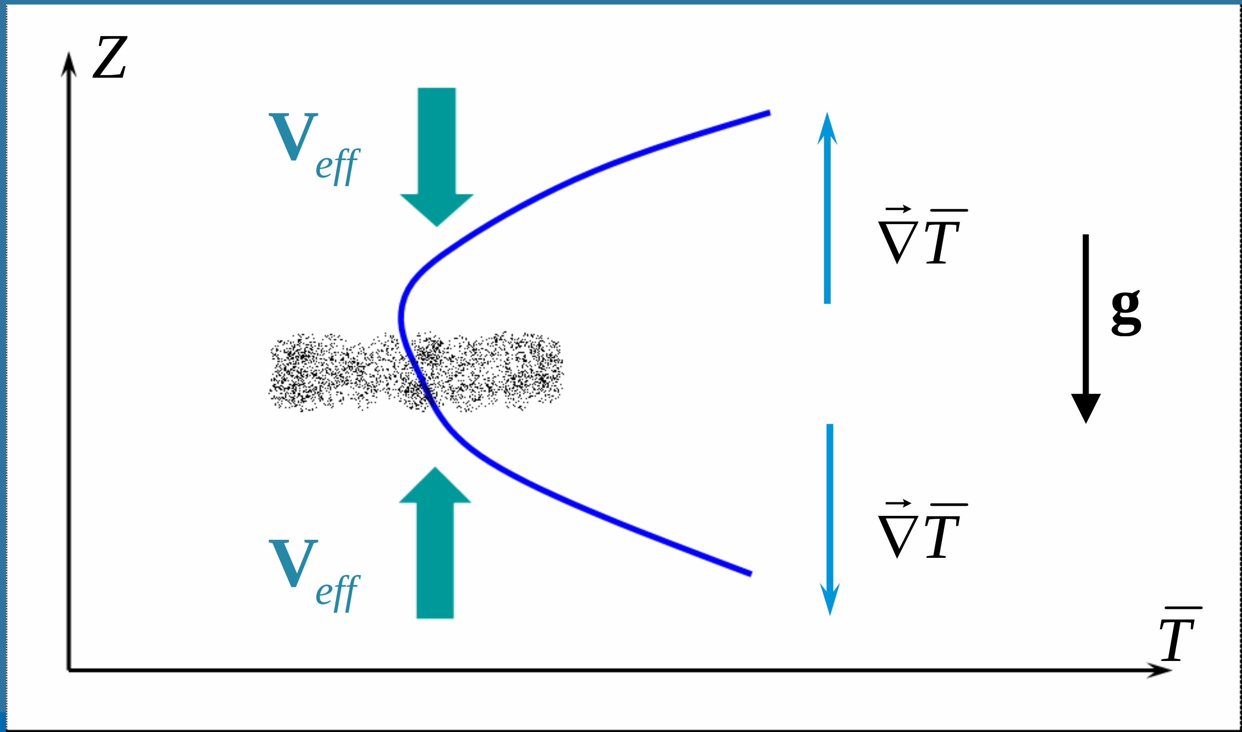
Distributions of Number density of aerosols and Mean Temperature (Satellite Data of "Junge" Aerosol Layer)



Distribution of Number density of aerosols
Mean Temperature Distribution
(Satellite Data of "Junge" Aerosol Layer)



Turbulent Thermal Diffusion



$$\mathbf{V}_p = \overline{\mathbf{V}} + \mathbf{g}\,\tau_p + \mathbf{V}_{eff}$$

$$\mathbf{V}_{eff} \propto -\frac{1}{\mathrm{Pe}}\frac{m_p}{m_\mu}\ln \mathrm{Re}\,\frac{\vec{\nabla}\overline{T}}{\overline{T}_*}$$

The ratio $\left|\mathbf{V}_{eff}/W\right|$ for typical atmospheric parameters (different temperature gradients and different particle sizes)

a_*	1 K / 100 m	1 K / 200 m	1 K / 300 m
1 μm	13	6.5	4.33
5 μm	3.4	1.7	1.13
10 – 20 μm	3	1.5	1
30 μm	2.7	1.35	0.9

The ratio $\left|\mathbf{V}_{eff}/W\right|$ for typical atmospheric parameters (different temperature gradients and different particle sizes)

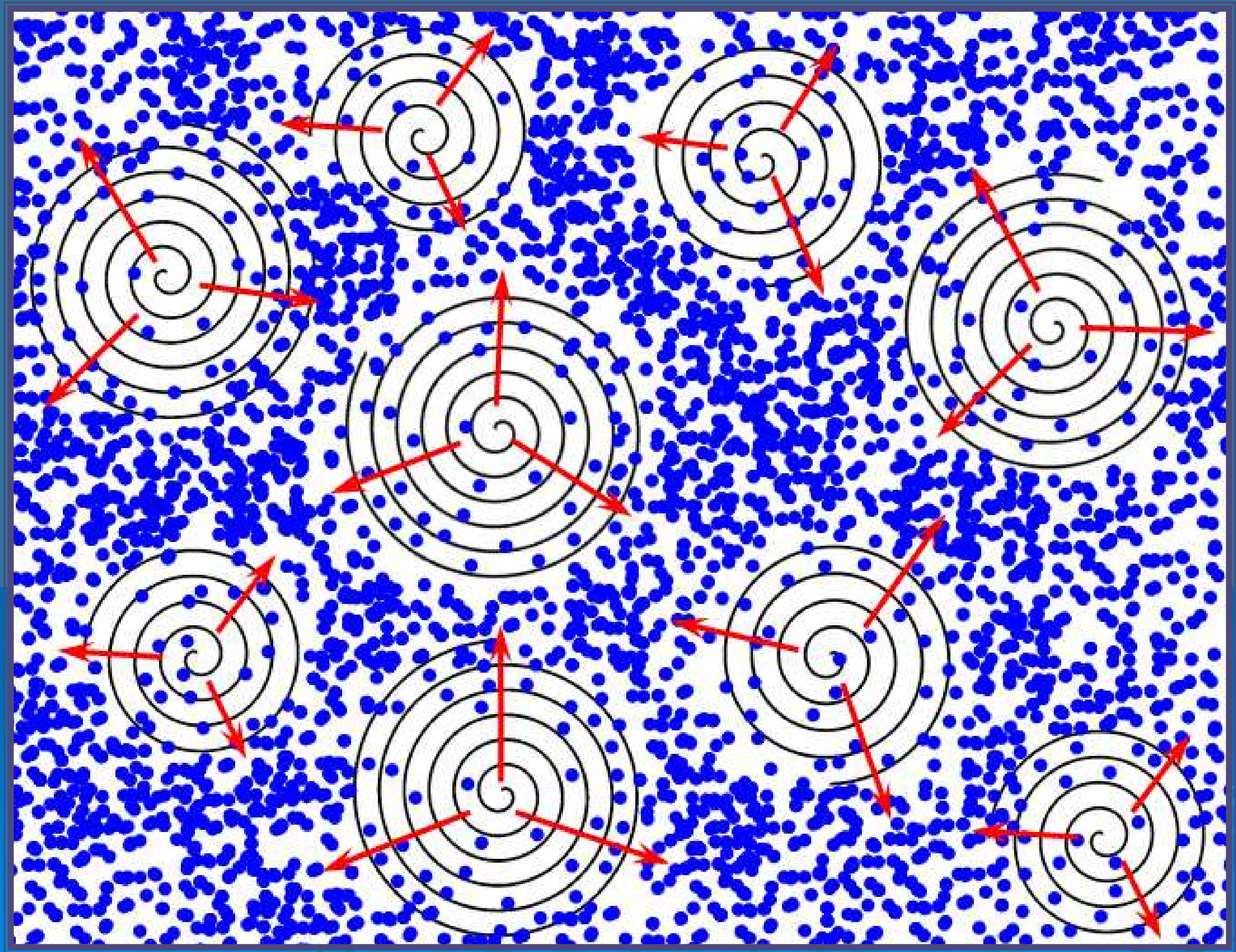
	1 K/100 m	1 K/200 m	1 K/300 m	1 K/1000 m
$a_* = 30$ μm	2.7	1.35	0.9	0.27
$a_* = 50$ μm	2.43	1.22	0.81	0.243
$a_* = 100$ μm	2.06	1.03	0.687	0.206
$a_* = 200$ μm	1.7	0.85	0.567	0.17
$a_* = 300$ μm	1.5	0.75	0.5	0.15
$a_* = 500$ μm	1.2	0.6	0.4	0.12

Time of Formation of Aerosol Layers

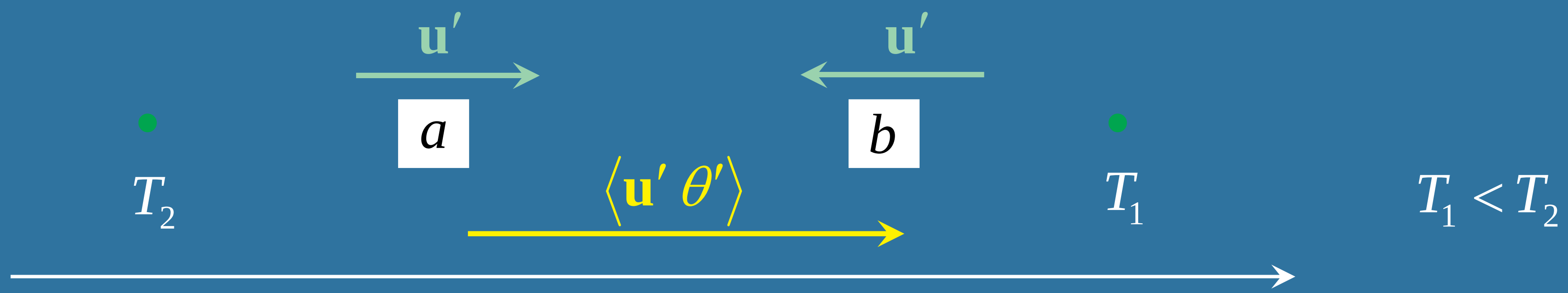
	1 K/100 m	1 K/200 m
$a_* = 30\ \mu m$	11 min	105 min
$a_* = 100\ \mu m$	1 min	120 min

$$t \propto \frac{L_T}{\left|\mathbf{V}_{eff} - \mathbf{W}\right|}$$

Particle Inertia Effect



Turbulent Thermal Diffusion



	$u' > 0$	$u' < 0$
$u' \theta' > 0 \;\Rightarrow$	$\theta' > 0$	$\theta' < 0 \;\Leftarrow\; u' \theta' > 0$
	$\Downarrow$	$\Downarrow$
	$p' > 0$	$p' < 0$
	$\Downarrow$	$\Downarrow$
$u' n' > 0 \;\Leftarrow$	$n' > 0$	$n' < 0 \;\Rightarrow\; u' n' > 0$

$\langle \mathbf{u}' n' \rangle \longrightarrow$

Non-diffusive mean flux of particles is in the direction of the mean heat flux (i.e., in the direction of minimum fluid temperature).

Turbulent thermal diffusion of particles

$$\frac{\partial n}{\partial t} + \mathrm{div}\left(n \mathbf{v}_p\right) = -\nabla \cdot \mathbf{J}_M$$

Averaging over turbulent velocity field

$$\frac{\partial \overline{N}}{\partial t} + \mathrm{div}\left(\overline{N}\, \overline{\mathbf{V}}_p\right) = -\mathrm{div}\left(\overline{\mathbf{J}}_T + \overline{\mathbf{J}}_M\right)$$

$$\overline{N} \equiv \langle n \rangle$$

$$\mathbf{v}_p = \overline{\mathbf{V}}_p + \mathbf{u}, \quad \overline{\mathbf{V}}_p = \langle \mathbf{v}_p \rangle$$

$$\overline{\mathbf{J}}_T = \overline{N}\, \mathbf{V}_{eff} - \mathbf{D}_T \nabla \overline{N}$$

$$\mathbf{V}_{eff} = -\tau \langle \mathbf{u}\, \mathrm{div}\, \mathbf{u} \rangle$$

$$[\overline{N}] \to \mathrm{cm}^{-3}$$

Turbulent flux of particles

$$\frac{\partial n'}{\partial t} - D\Delta n' + \operatorname{div}\mathbf{Q} = -\operatorname{div}\left(\overline{N}\mathbf{u}\right)$$

$$n = \overline{N} + n' \qquad \mathbf{Q} = \mathbf{u}\,n' - \langle \mathbf{u}\,n' \rangle$$

$$n' \sim -\tau\,\overline{N}\left(\operatorname{div}\mathbf{u}\right) - \tau\left(\mathbf{u}\cdot\nabla\right)\overline{N}$$ - fluctuations of particles number density

$$\mathbf{J}_T \equiv \langle \mathbf{u}\,n' \rangle \sim -\overline{N}\tau\langle \mathbf{u}\operatorname{div}\mathbf{u}\rangle - \tau\langle \mathbf{u}\left(\mathbf{u}\cdot\nabla\right)\rangle\overline{N}$$

$$\mathbf{D}_T = \tau\left\langle \mathbf{u}^2 \right\rangle$$ - turbulent diffusion

$$\mathbf{V}_{eff} = -\tau\langle \mathbf{u}\operatorname{div}\mathbf{u}\rangle$$ - effective velocity

$$\mathbf{J}_T = \overline{N}\,\mathbf{V}_{eff} - D_T\nabla\overline{N}$$ - turbulent flux of particles

Turbulent thermal diffusion of non-inertial particles

$$\mathbf{V}_p = \mathbf{u}$$

$$\rho \operatorname{div} \mathbf{u} + \mathbf{u} \cdot \nabla \rho \approx 0$$

$$\operatorname{div} \mathbf{u} \approx -\mathbf{u} \cdot \frac{\nabla \rho}{\rho}$$

Equation of state for ideal gas yields:

$$\frac{\nabla \bar{\rho}}{\bar{\rho}} \approx -\frac{\nabla \bar{T}}{\bar{T}}$$

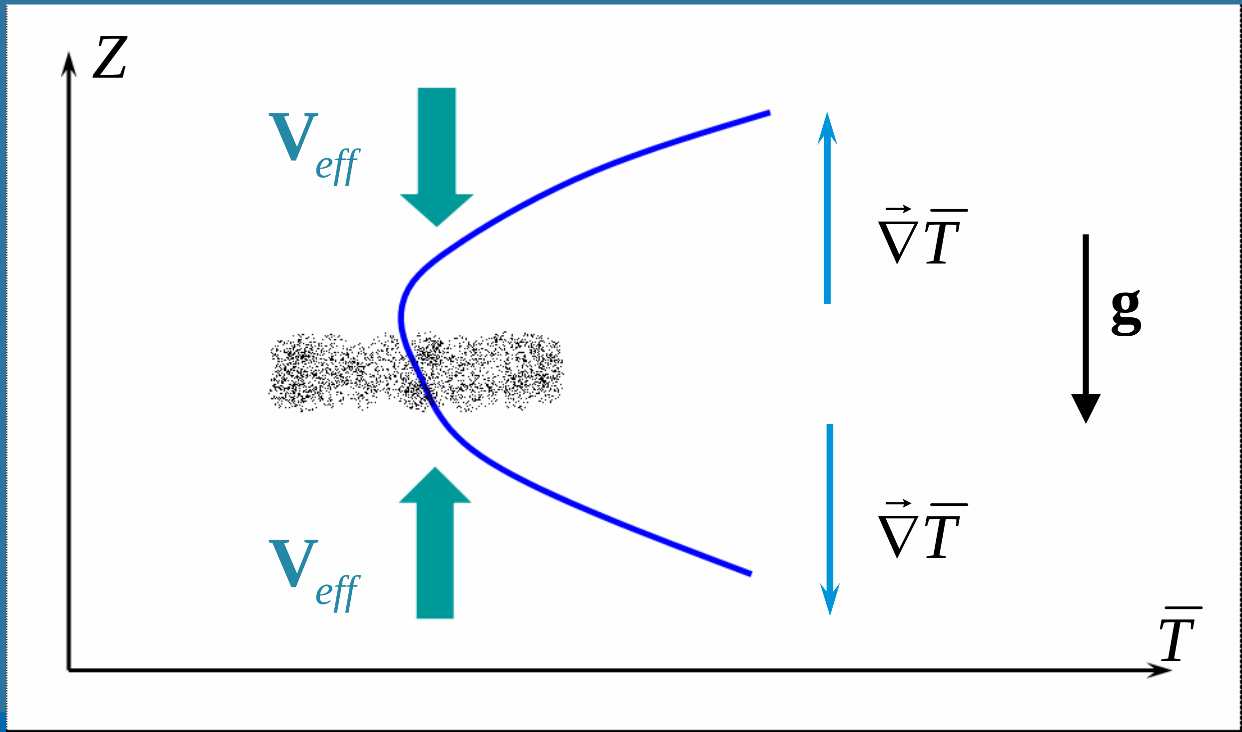
$$\frac{\partial \bar{N}}{\partial t} + \operatorname{div}\left(\bar{N}\, \mathbf{V}_{eff} - D_T \nabla \bar{N}\right) = 0$$

$$\mathbf{V}_{eff} = -\tau \langle \mathbf{u} \operatorname{div} \mathbf{u} \rangle$$

$$-\tau \langle u_i \operatorname{div} \mathbf{u} \rangle = \tau \langle u_i u_j \rangle \frac{\nabla_j \bar{\rho}}{\bar{\rho}} = D_T \frac{\nabla_i \bar{\rho}}{\bar{\rho}}$$

$$\mathbf{V}_{eff} = D_T \frac{\nabla \bar{\rho}}{\bar{\rho}} = -D_T \frac{\nabla \bar{T}}{\bar{T}}$$

Turbulent Thermal Diffusion



$$\mathbf{V}_p = \overline{\mathbf{V}} + \mathbf{g}\,\tau_p + \mathbf{V}_{eff}$$

$$\mathbf{V}_{eff} = -D_T \frac{\vec{\nabla}\overline{T}}{\overline{T}}$$

Turbulent Thermal Diffusion of non-inertial particles or gases

$$\frac{\partial \overline{N}}{\partial t} + \mathrm{div}\left(\overline{N}\,\mathbf{V}_{eff} - D_T \nabla \overline{N}\right) = 0$$

$$\mathbf{V}_{eff} = -D_T \frac{\nabla \overline{T}}{\overline{T}} = D_T \frac{\nabla \overline{\rho}}{\overline{\rho}}$$

Steady state:

$$\frac{\nabla \overline{N}}{\overline{N}} = -\frac{\nabla \overline{T}}{\overline{T}}$$

$$\overline{N}\,\overline{T} = const$$

$$\frac{\overline{N}}{\overline{\rho}} = const$$

Turbulent thermal diffusion of inertial particles

$$\frac{d\,\mathbf{v}_p}{d\,t} = -\frac{\mathbf{v}_p - \mathbf{v}}{\tau_p}$$

$$\tau_\mathrm{p} = \frac{\mathrm{m_p}}{6\pi\,\rho\,\nu\,a_*} \propto a_*^2$$

$$\mathbf{v}_p = \mathbf{v} - \tau_p \frac{d\mathbf{v}}{dt} + O\left(\tau_p^2\right)$$

$$\mathrm{div}\,\mathbf{v}_p = \mathrm{div}\,\mathbf{v} + \tau_p \frac{\Delta P}{\rho} + O\left(\tau_p^2\right)$$

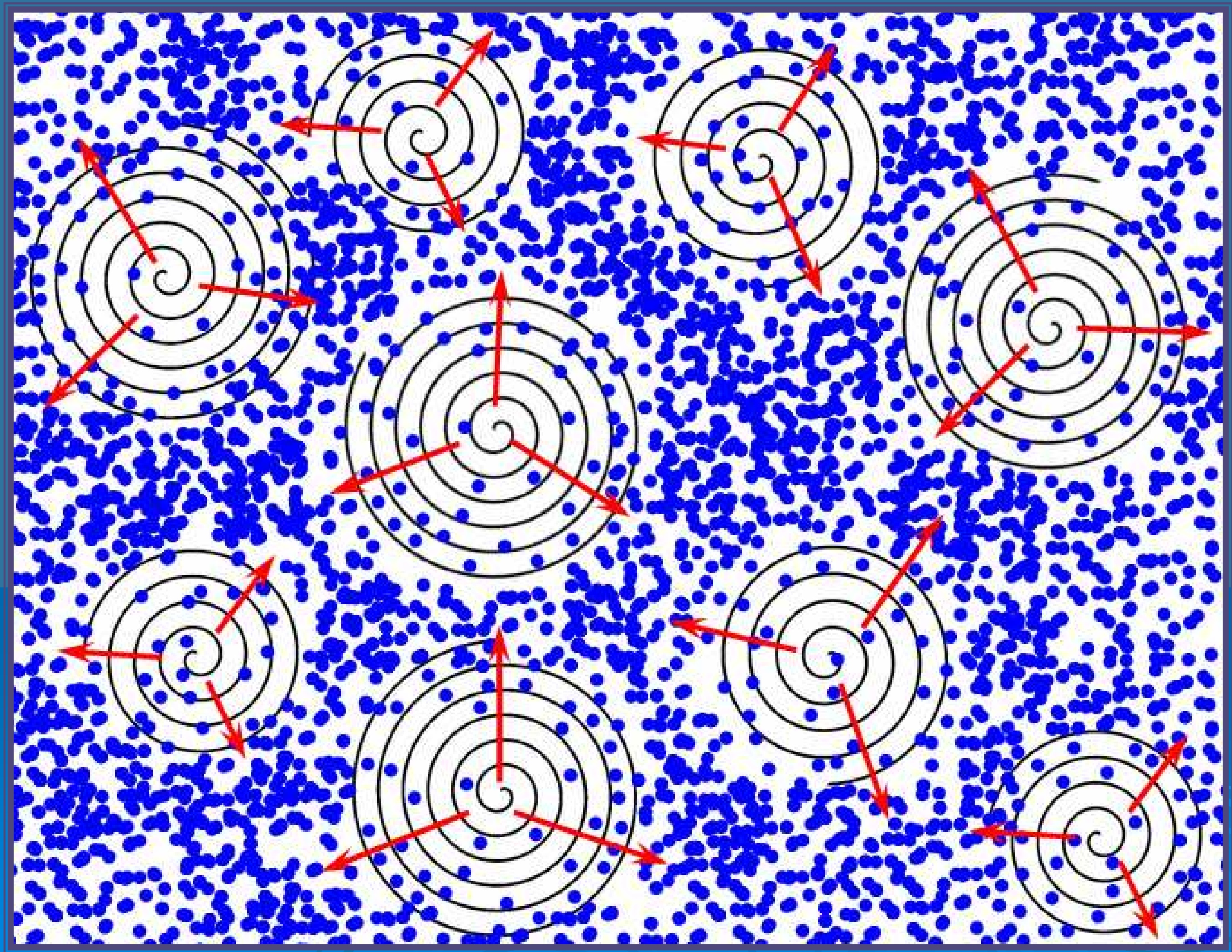
$$\mathbf{V}_{\mathrm{eff}} = -\mathrm{D_T}\,\alpha\,\frac{\vec{\nabla}\bar{T}}{\bar{T}}$$

$$\alpha = 1 + \frac{3}{Pe}\left(\frac{m_p}{m_\mu}\right)\left(\frac{\bar{T}}{T_*}\right)\ln\left(Re\right)$$

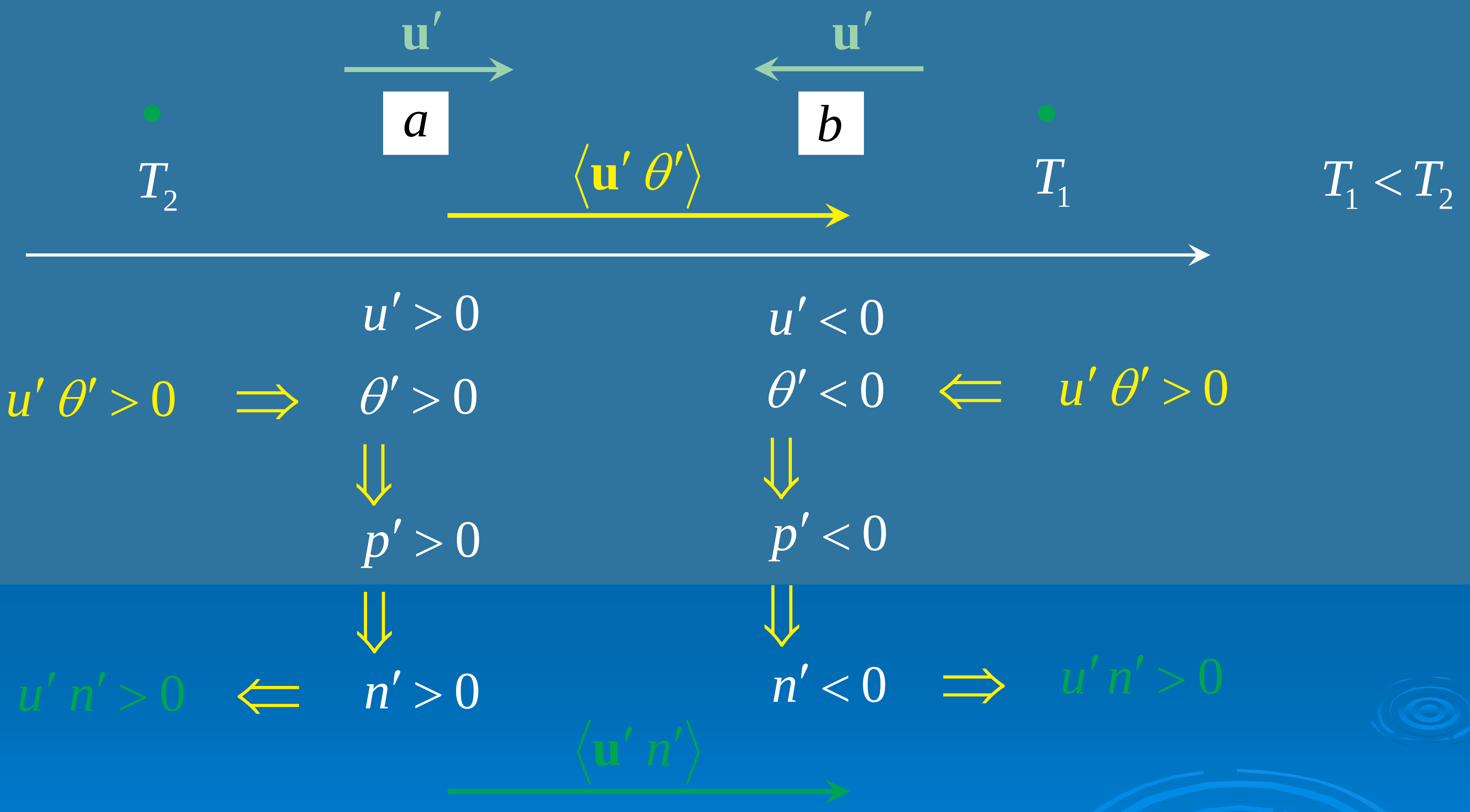
Steady state:

$$\bar{N}\,\bar{T}^{\alpha} = const$$

Particle Inertia Effect



Turbulent Thermal Diffusion



Non-diffusive mean flux of particles is in the direction of the mean heat flux (i.e., in the direction of minimum fluid temperature).

Derivation of the effect of turbulent thermal diffusion

• Stochastic calculus and Wiener path integral representation of solution of convective diffusion equation: Feynmann-Kac formula and Cameron-Martin-Girsanov theorem.

• The spectral tau approximation.

T. Elperin, N. Kleeorin and I. Rogachevskii

- Physical Review Letters **76**, 224 (1996)
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- Physical Review Letters **80**, 69 (1998)
- International Journal of Multiphase Flow **24**, 1163 (1998)
- Physical Review E **58**, 3113 (1998)
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- Physical Review E **61**, 2617 (2000)
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- Physical Review E**64**, 026304 (2001)

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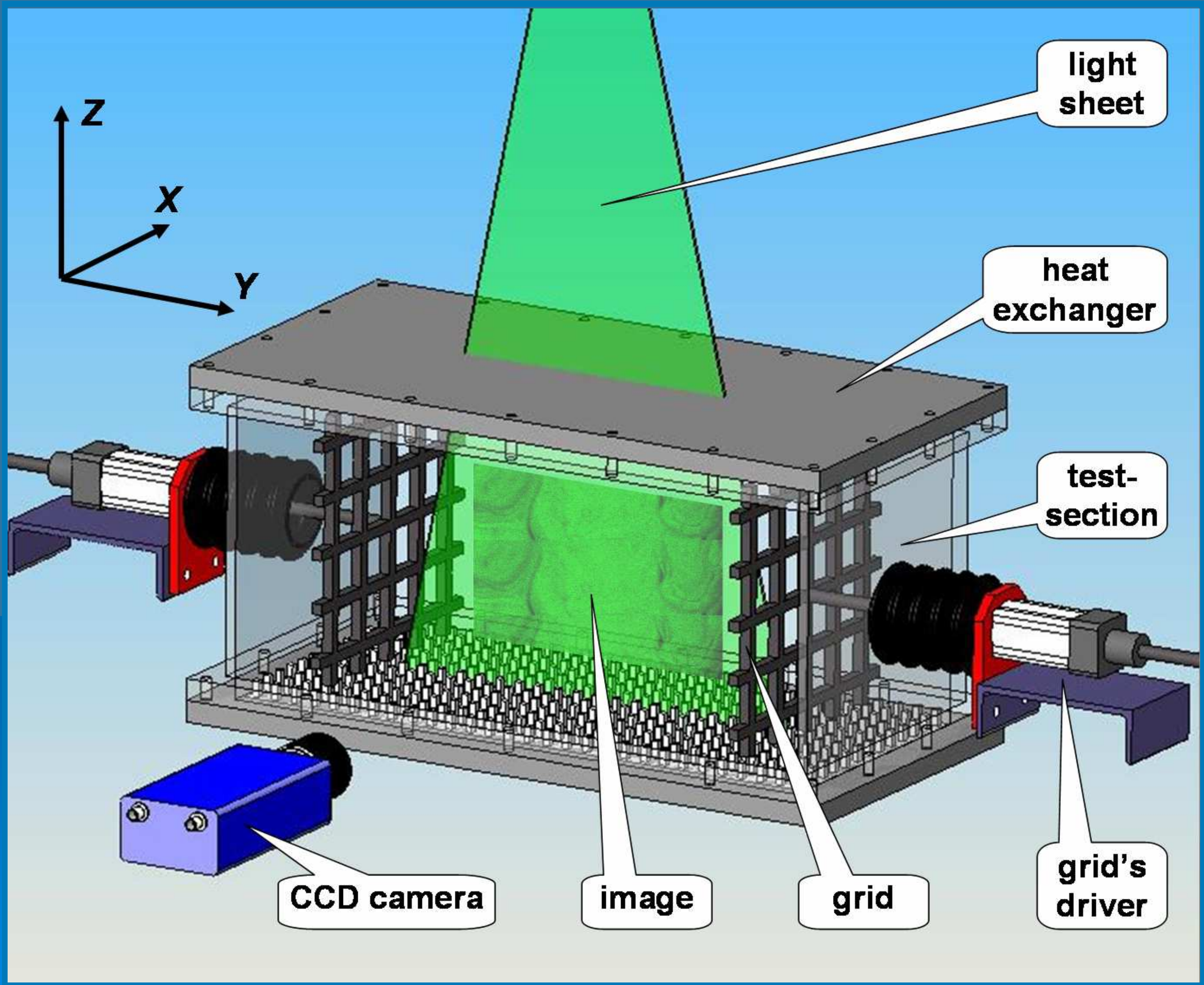
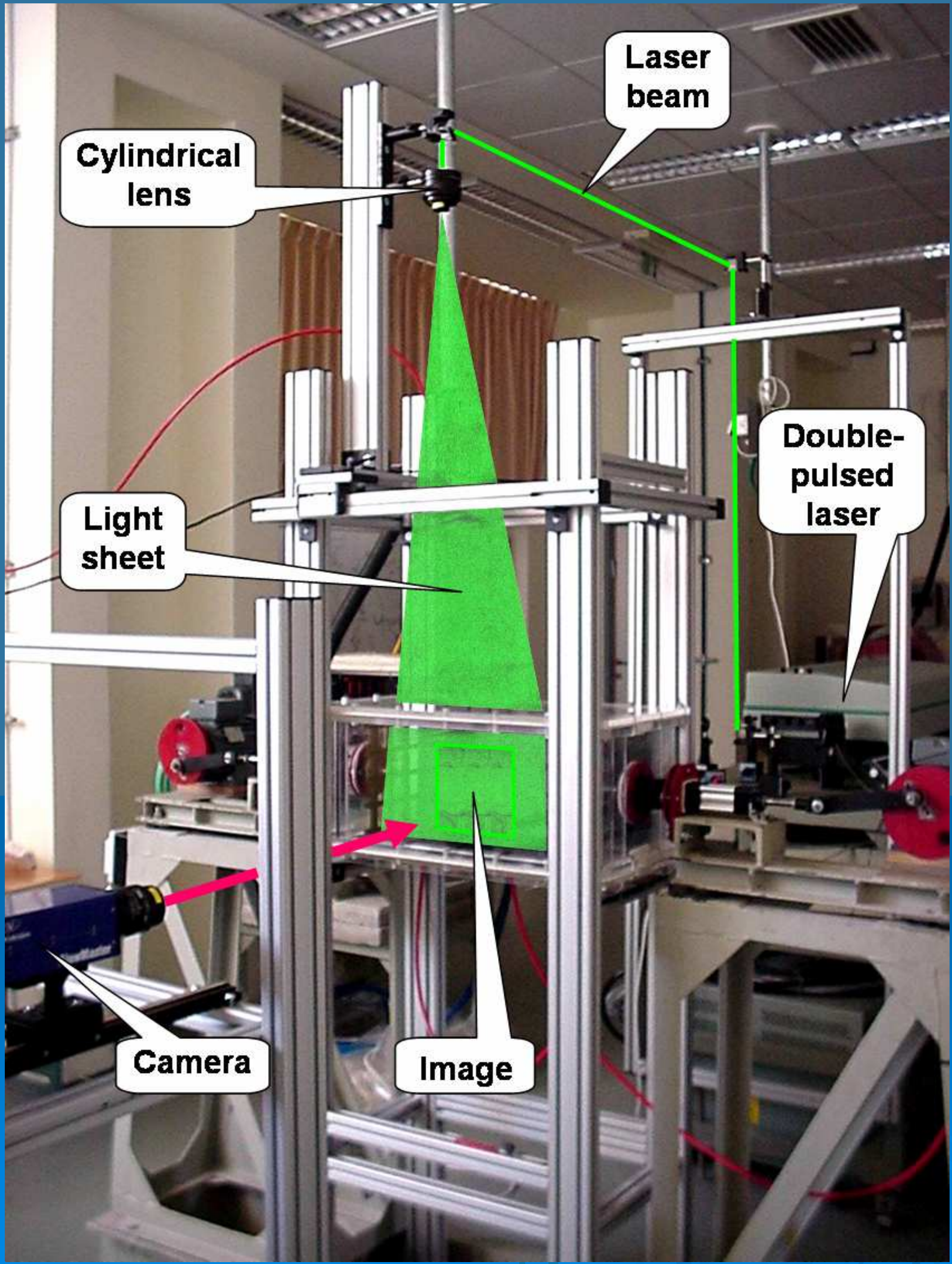
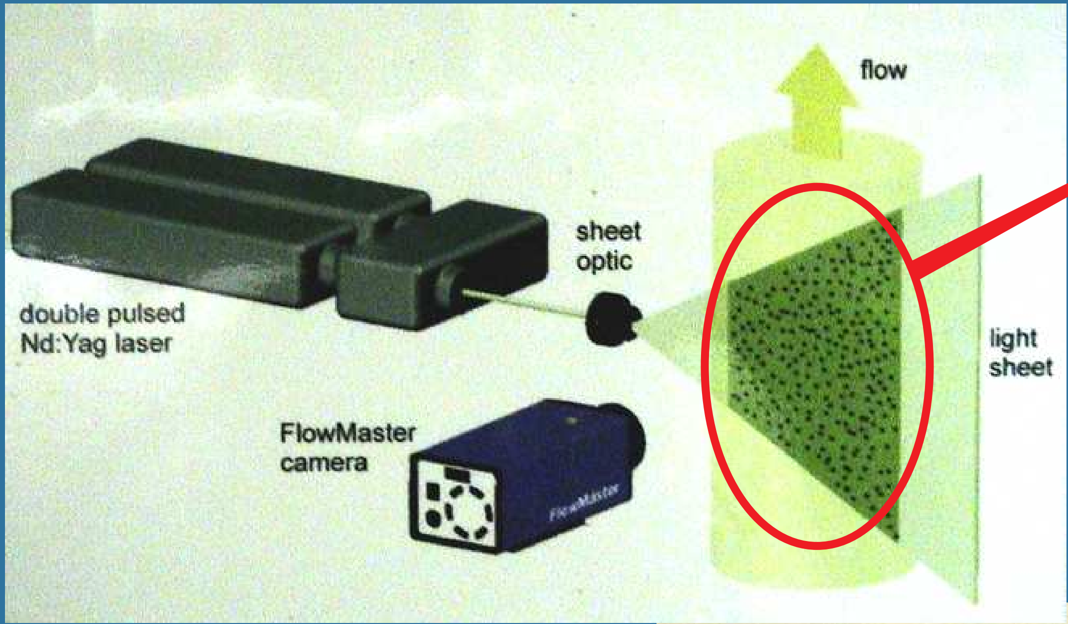
Experimental Set–up

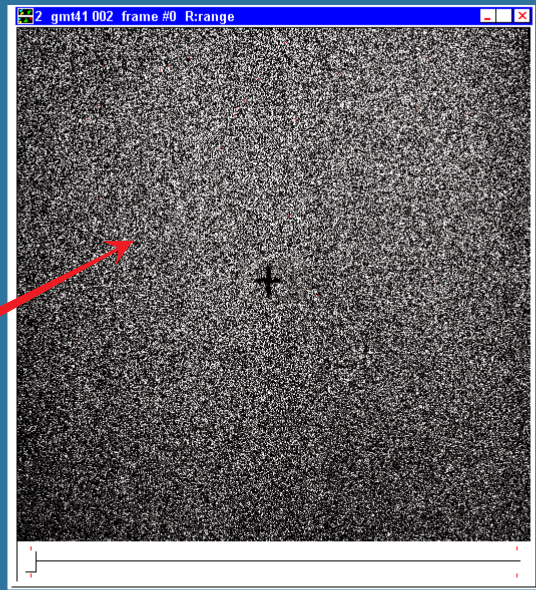




Experimental set - up: oscillating grids turbulence generator and particle image velocimetry system

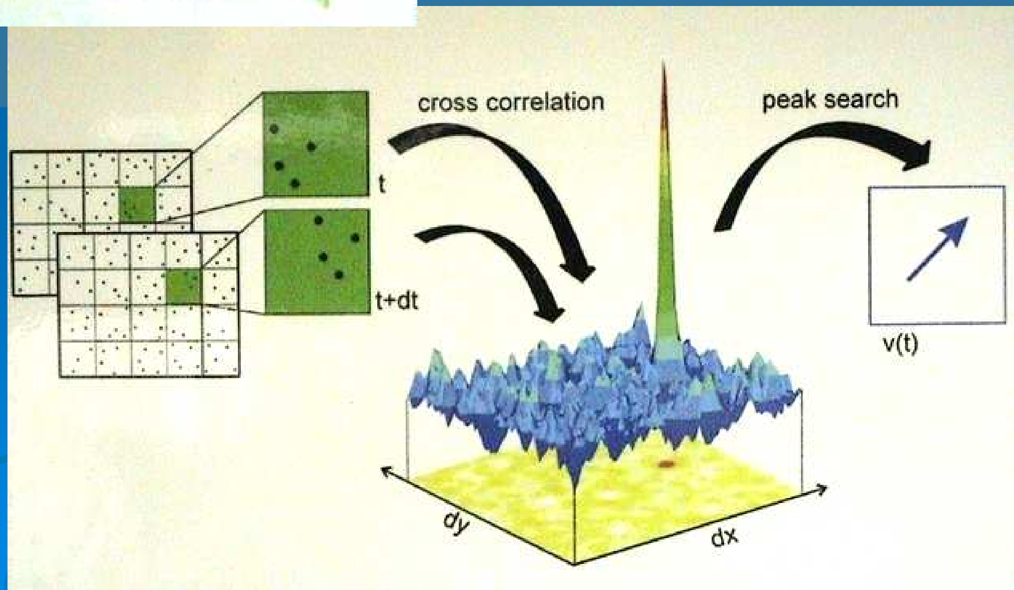
Particle Image Velocimetry System



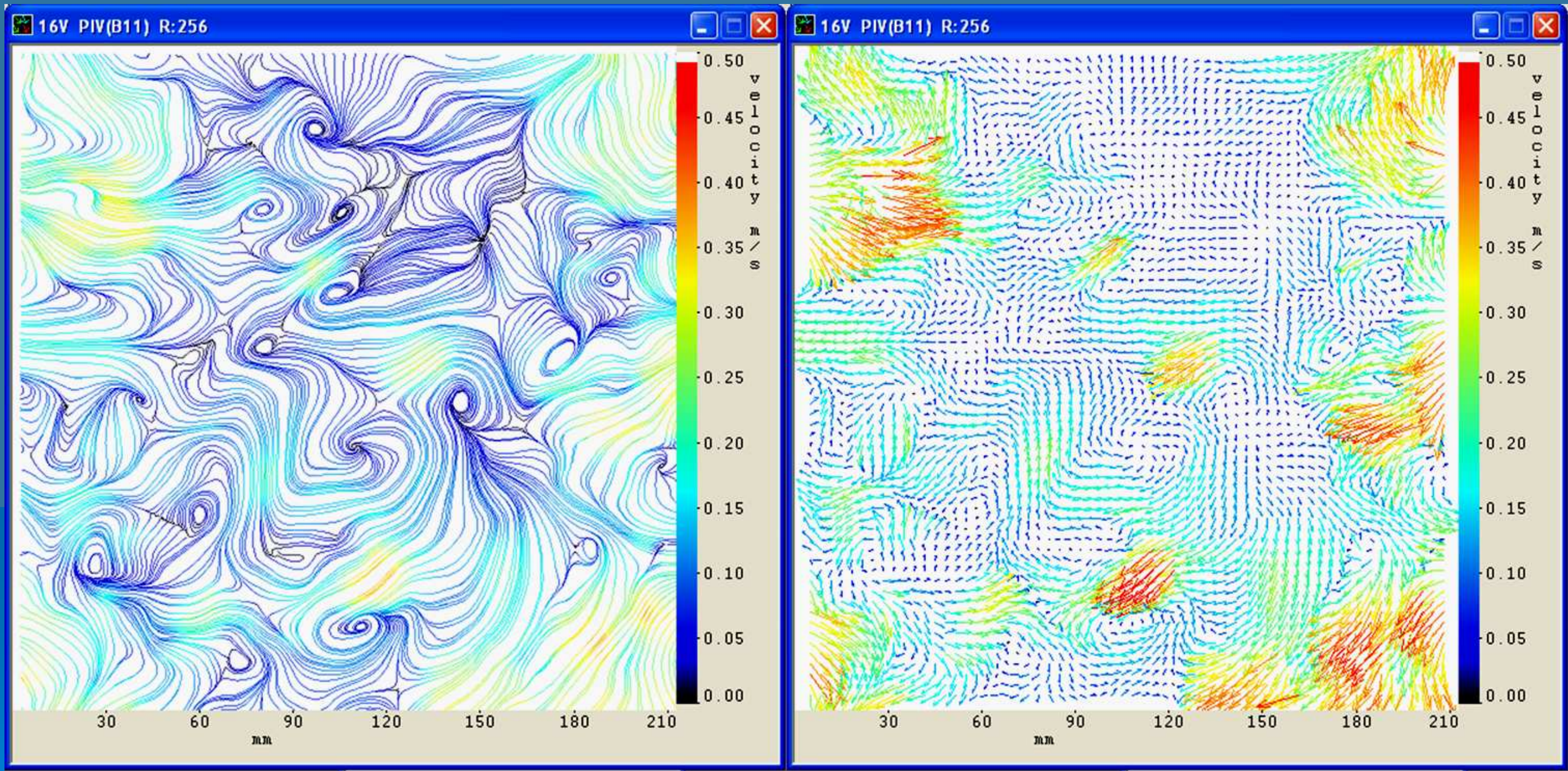


Raw image of the incense smoke tracer particles in oscillating grids turbulence

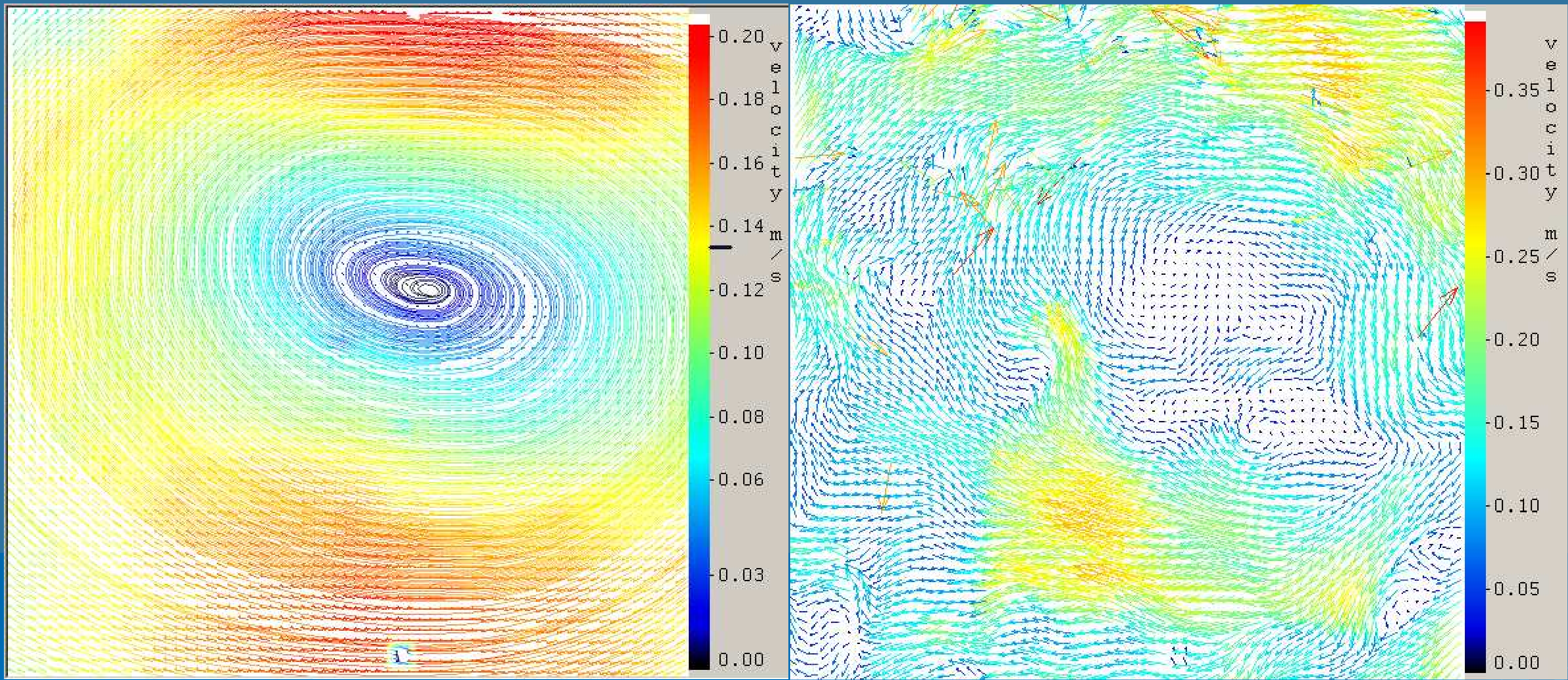
Particle Image Velocimetry Data Processing



Instantaneous Streamlines of the Flow and Velocity Map

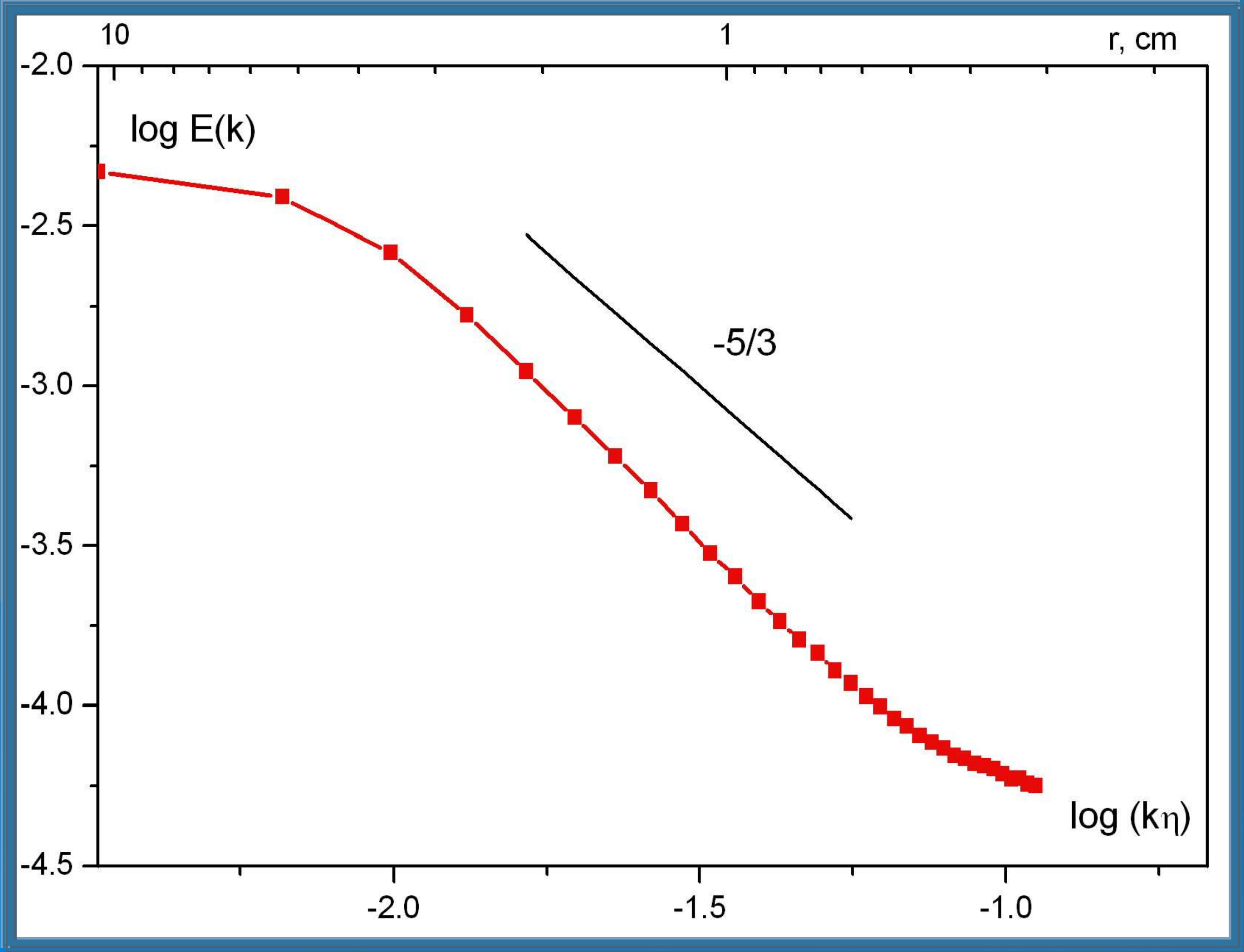


Velocity Fields

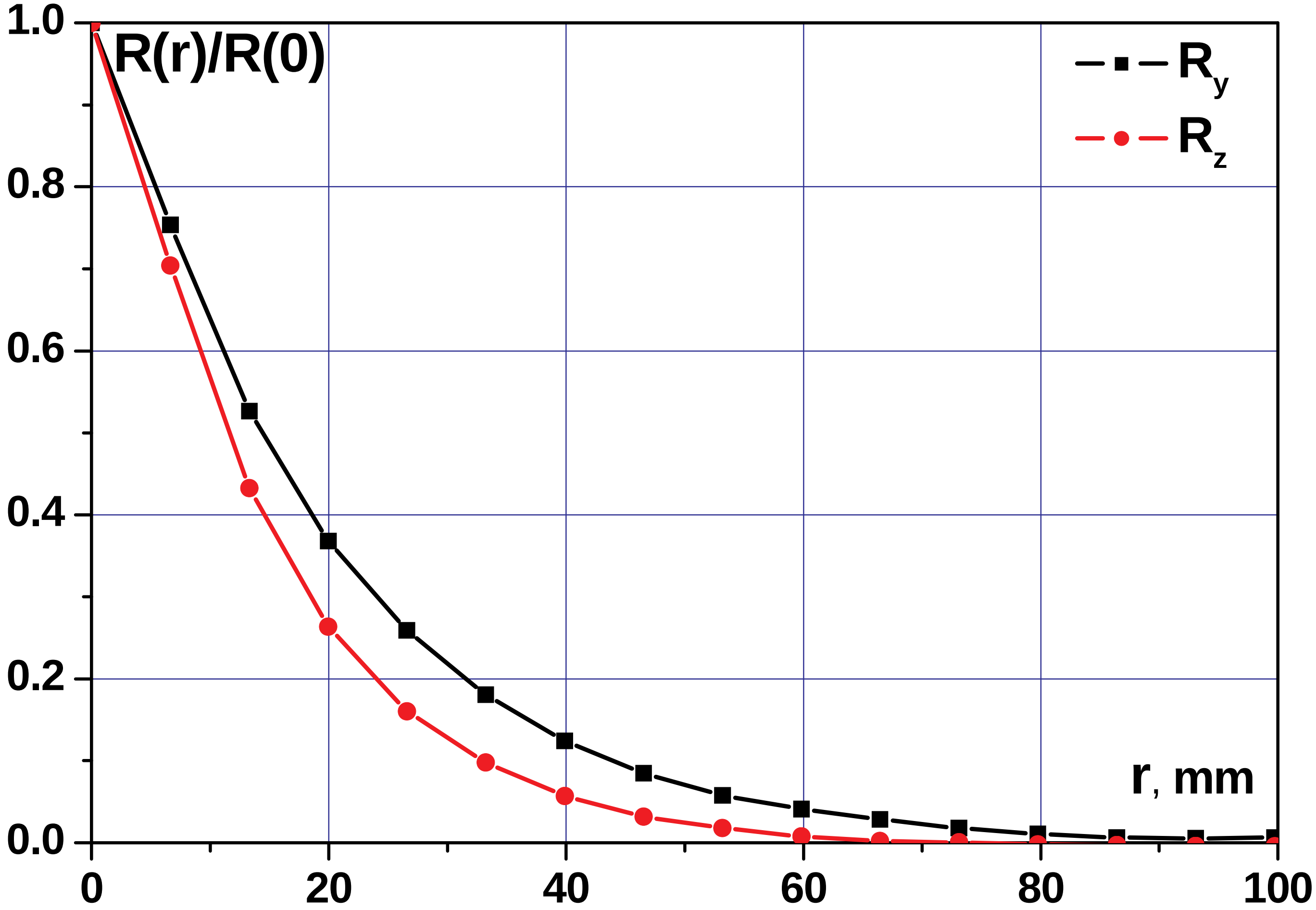


$$A = \frac{L_{\perp}^{B}}{L_{z}^{B}} = 1$$

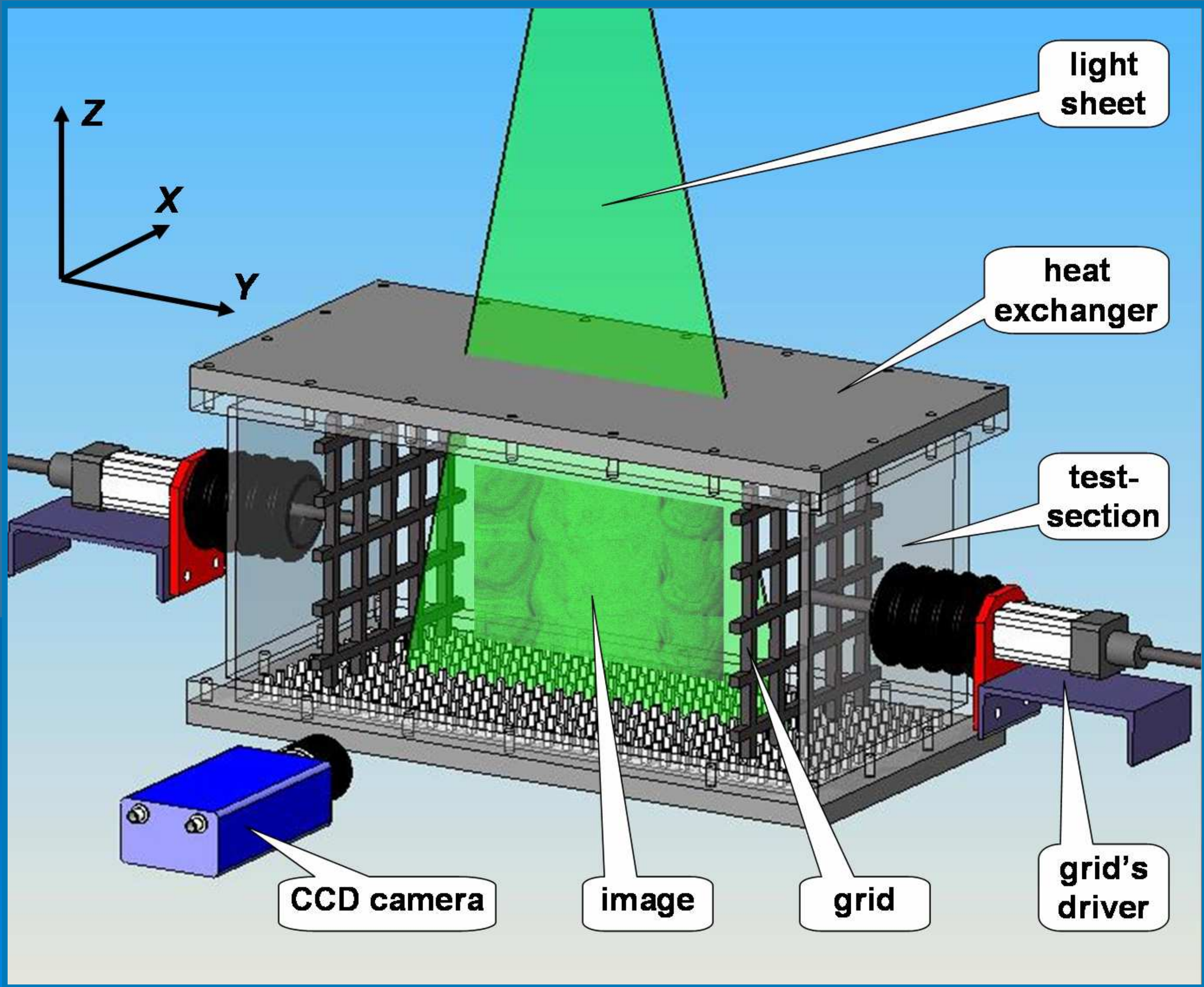
Turbulent Energy Spectrum



Longitudinal Correlation Functions



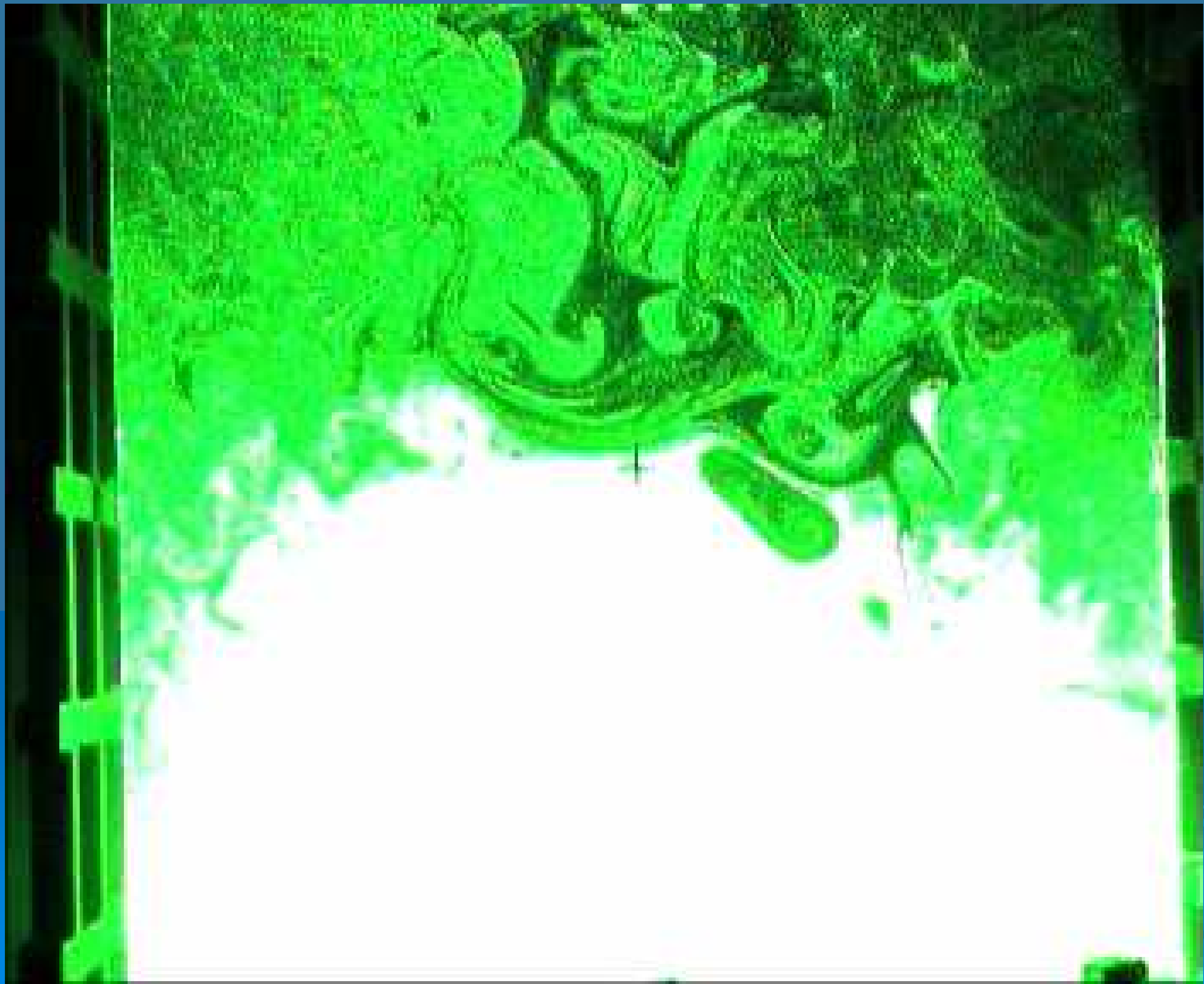
Experimental Set–up



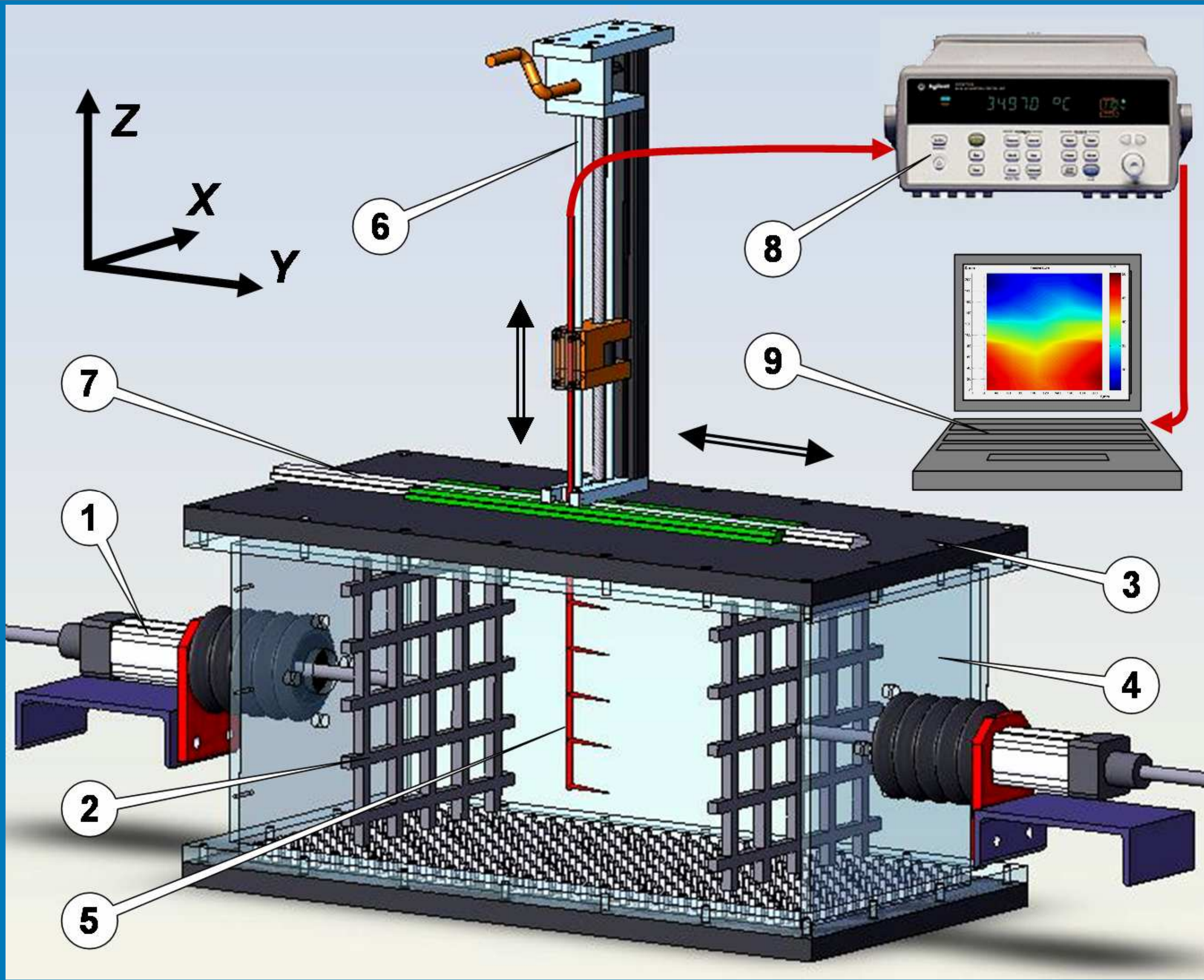
Characteristics of Oscillating Grids Turbulence in Isothermal and Non-isothermal Flows

Type of the flow	Isothermal	Stable stratification	Unstable stratification
R.m.s. velocity u(y), (cm/s)	10.2 ÷ 10.8	10.1 ÷ 11	10.7 ÷ 11.1
R.m.s. velocity u(z), (cm/s)	≈ 7.8	≈ 8	≈ 8.3
Integral scale L(y), (cm)	2.34 ÷ 2.5	2.41 ÷ 2.49	2.3 ÷ 2.52
Integral scale L(z), (cm)	1.57 ÷ 1.77	1.6 ÷ 1.76	1.5÷ 1.75
Reynolds number Re(y)	159 ÷ 180	162 ÷ 182	164 ÷ 186
Reynolds number Re(z)	82 ÷ 93	85 ÷ 94	83 ÷ 97
Turnover time τ, (ms)	≈ 230	≈ 230	≈ 230

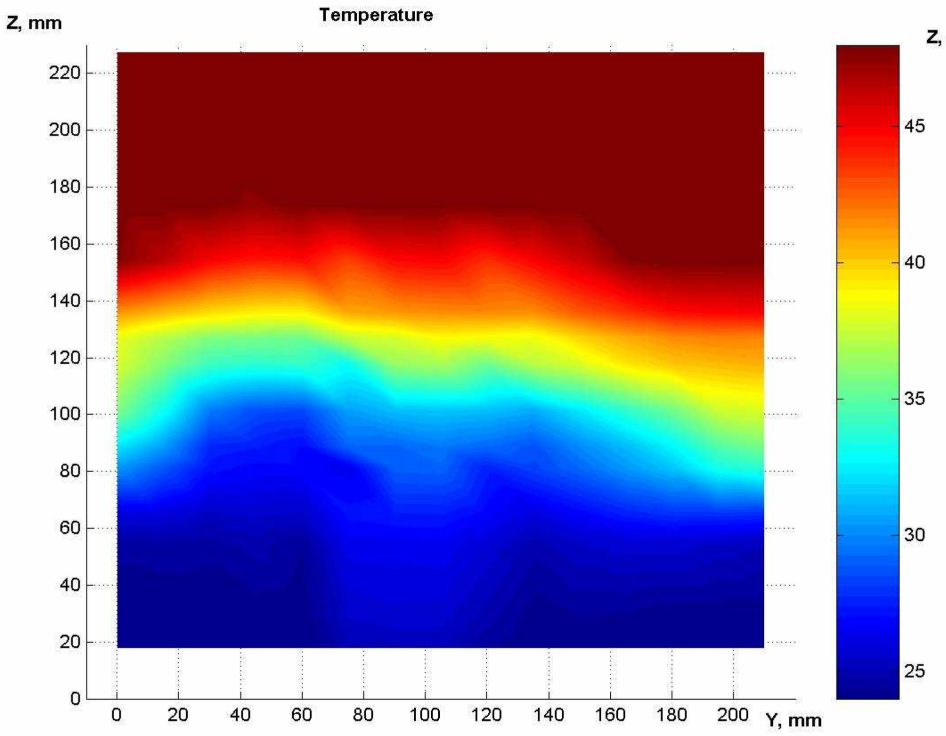
Flow Seeding

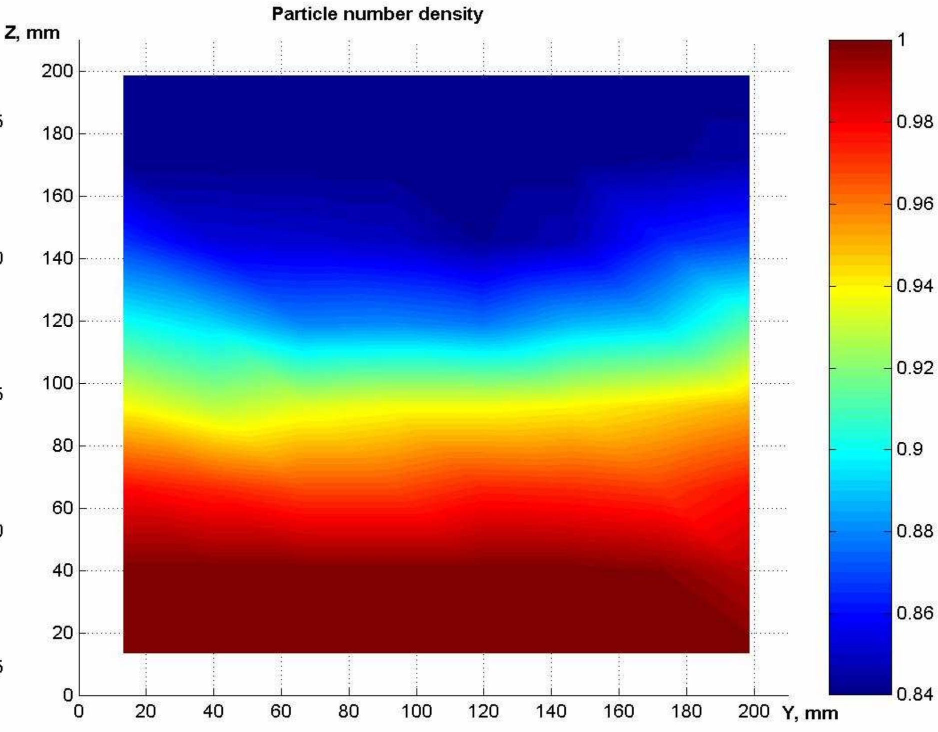


Experimental Set–up for Temperature Measurements



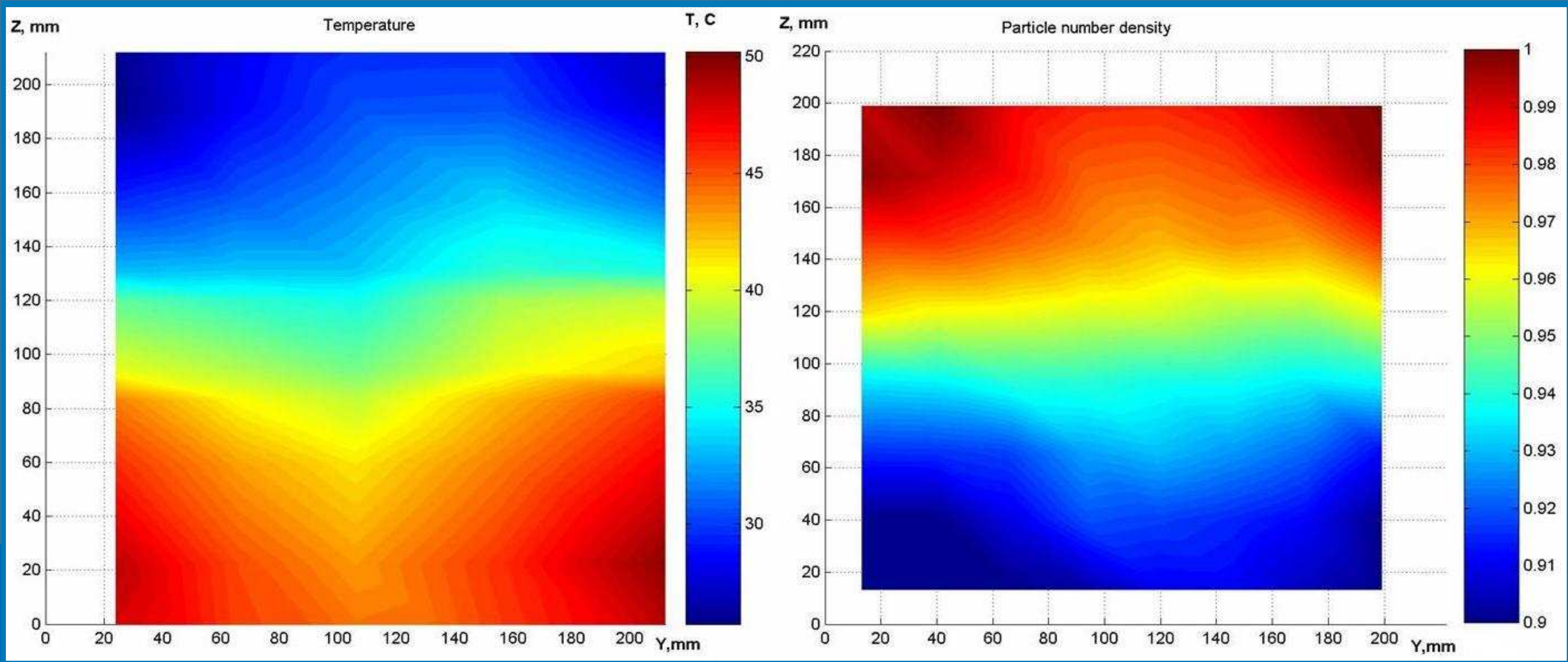
Temperature and Particle Number Density Fields. Stable Stratification





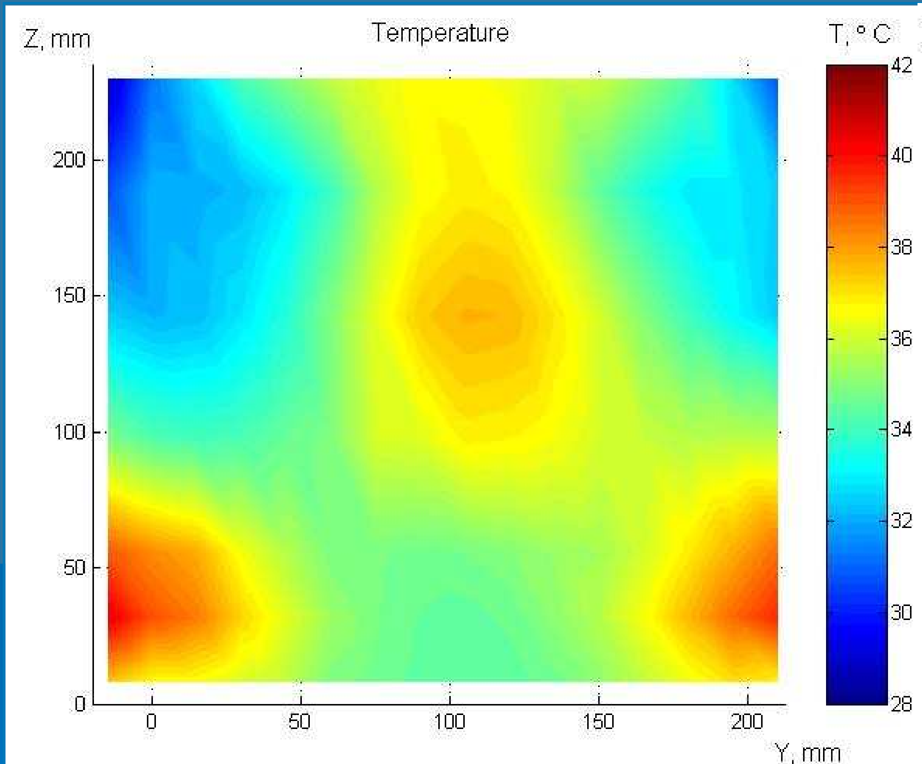
$\overline{T}(y,z)$ $\overline{N}(y,z)$

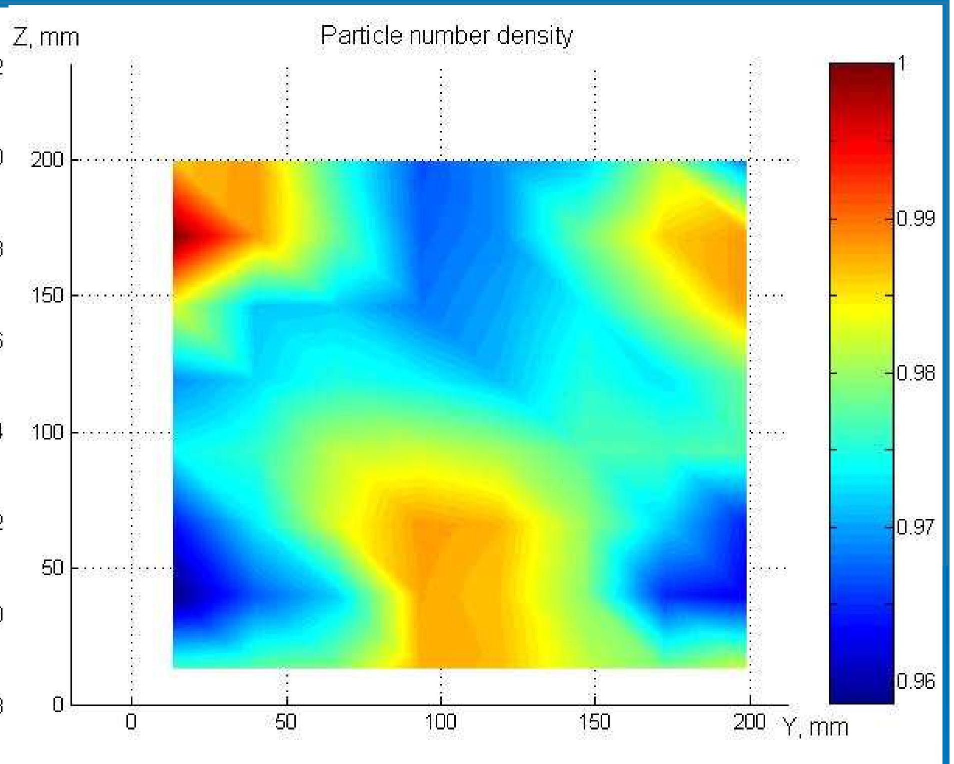
Temperature and Particle Number Density Fields. Unstable Stratification, f = 10.5 Hz



$\overline{T}(y,z)$ $\overline{N}(y,z)$

Temperature and Particle Number Density Fields. Unstable Stratification, f = 4.4 Hz

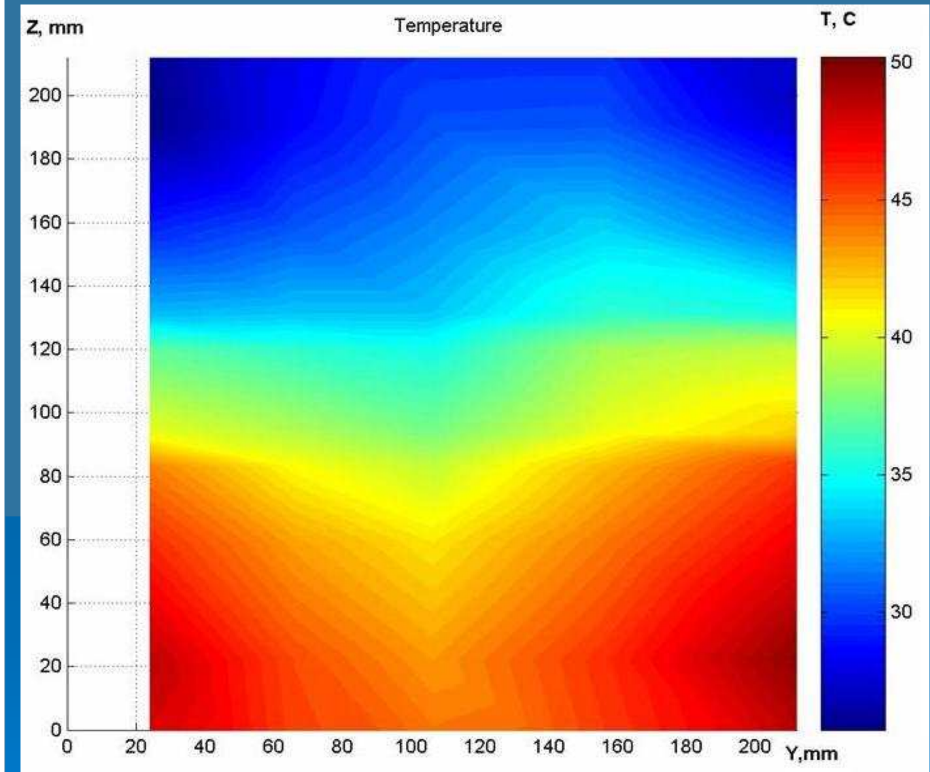


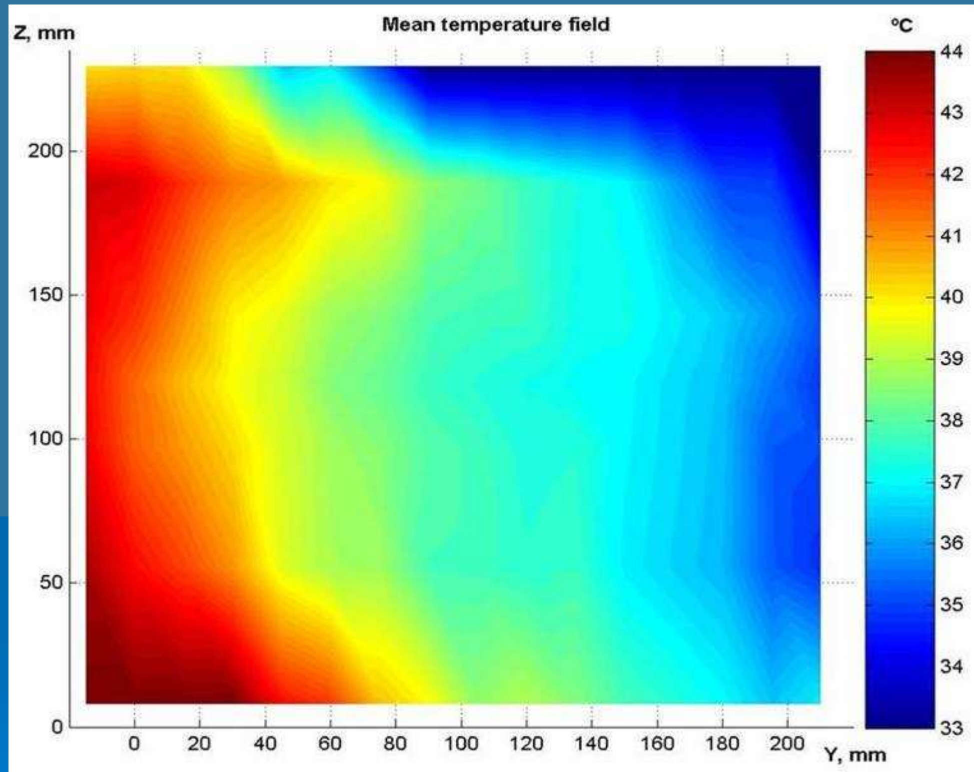


$\overline{T}(y,z)$

$\overline{N}(y,z)$

Temperature Field in Forced and Unforced Turbulent Convection

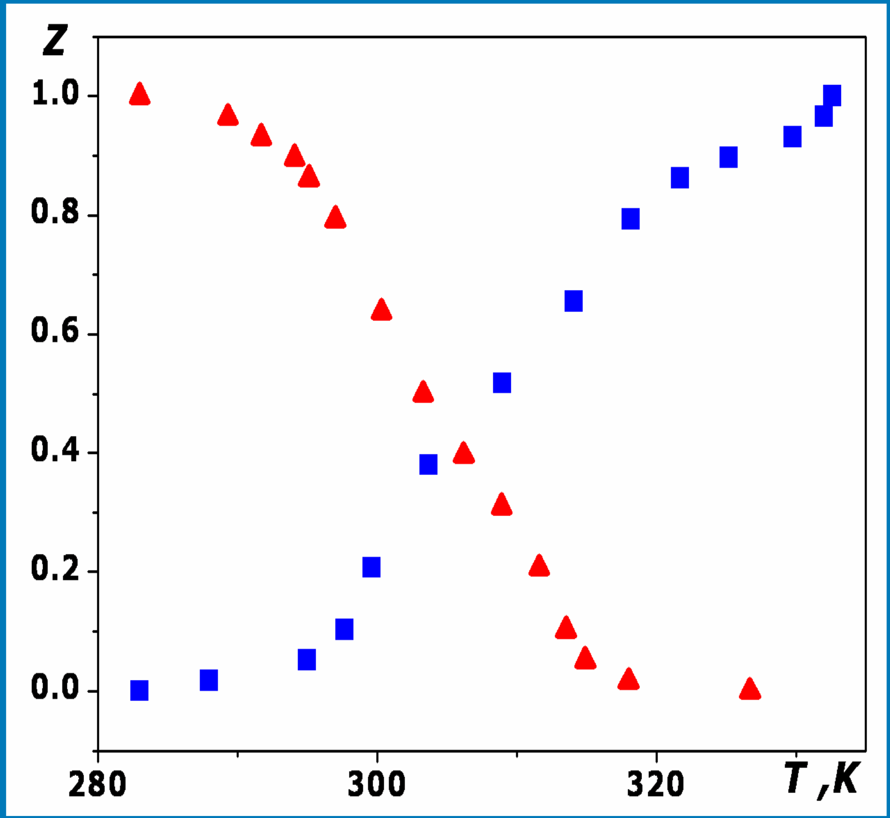




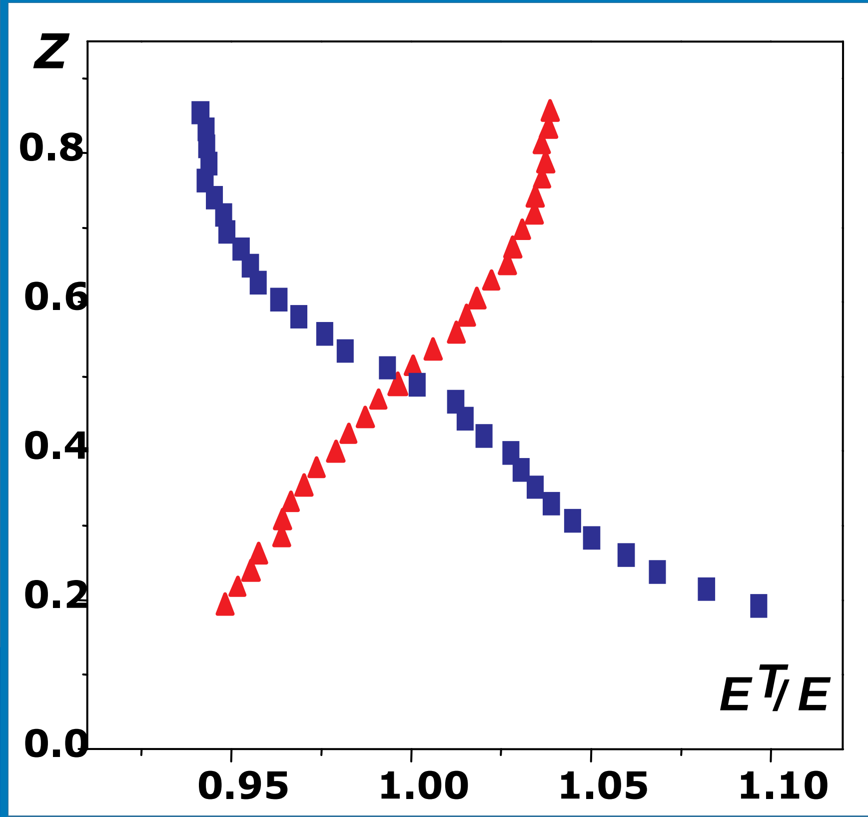
Forced turbulent convection (two oscillating grids)

Unforced convection

Temperature and Particle Spatial Distributions



$\overline{T}(z)$



$\overline{N}(z)$

■ - stable stratification

▲ - unstable stratification

Turbulent Thermal Diffusion

$$\frac{\partial \overline{N}}{\partial t} + \mathrm{div}\left(\overline{N}\,\mathbf{V}_{eff} - D_T \nabla \overline{N}\right) = 0$$

$$\mathbf{V}_{eff} = -D_T \alpha \frac{\nabla \overline{T}}{\overline{T}}$$

$\alpha = 1$ for non-inertial particles

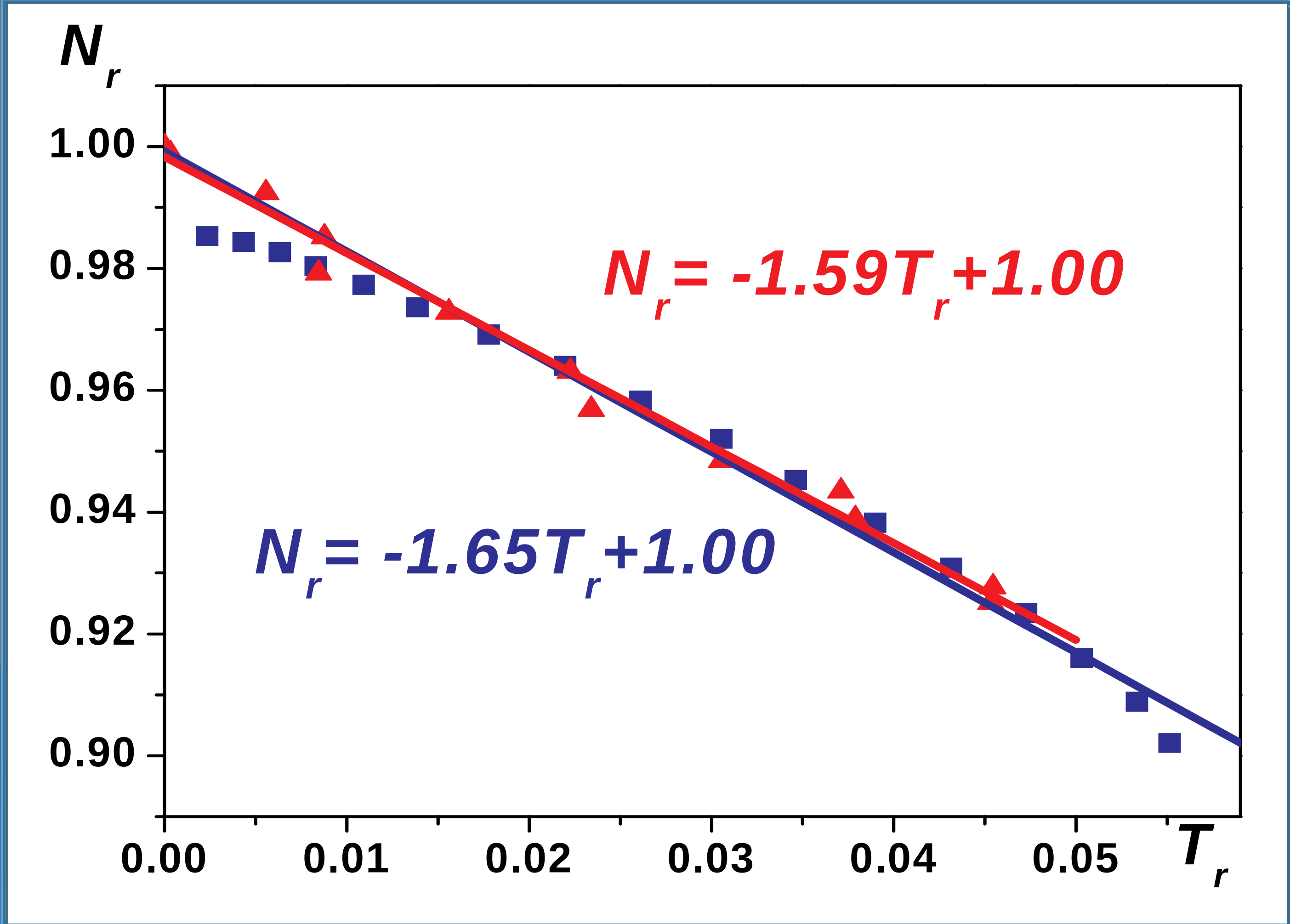
Steady state:

$$\frac{\nabla \overline{N}}{\overline{N}} = -\alpha \frac{\nabla \overline{T}}{\overline{T}}$$

$$\frac{\overline{N} - \overline{N}_0}{\overline{N}_0} = -\alpha \frac{\overline{T} - \overline{T}_0}{\overline{T}_0}$$

$$\frac{\overline{N}}{\overline{N}_0} = -\alpha \frac{\overline{T} - \overline{T}_0}{\overline{T}_0} + 1$$

Turbulent Thermal Diffusion



Normalized mean particle number density $N_r = \overline{N}/\overline{N}_0$ vs. normalized temperature gradient $T_r = (\overline{T}\text{-}\overline{T}_0)/\overline{T}_0$: ■ - stable stratification, ▲ - unstable stratification.

Turbulent thermal diffusion of inertial particles

$$\frac{d\,\mathbf{v}_p}{d\,t} = -\frac{\mathbf{v}_p - \mathbf{v}}{\tau_p}$$

$$\tau_\mathrm{p} = \frac{\mathrm{m_p}}{6\pi\,\rho\,\nu\,a_*} \propto a_*^2$$

$$\mathbf{v}_p = \mathbf{v} - \tau_p \frac{d\mathbf{v}}{dt} + O\left(\tau_p^2\right)$$

$$\mathrm{div}\,\mathbf{v}_p = \mathrm{div}\,\mathbf{v} + \tau_p \frac{\Delta P}{\rho} + O\left(\tau_p^2\right)$$

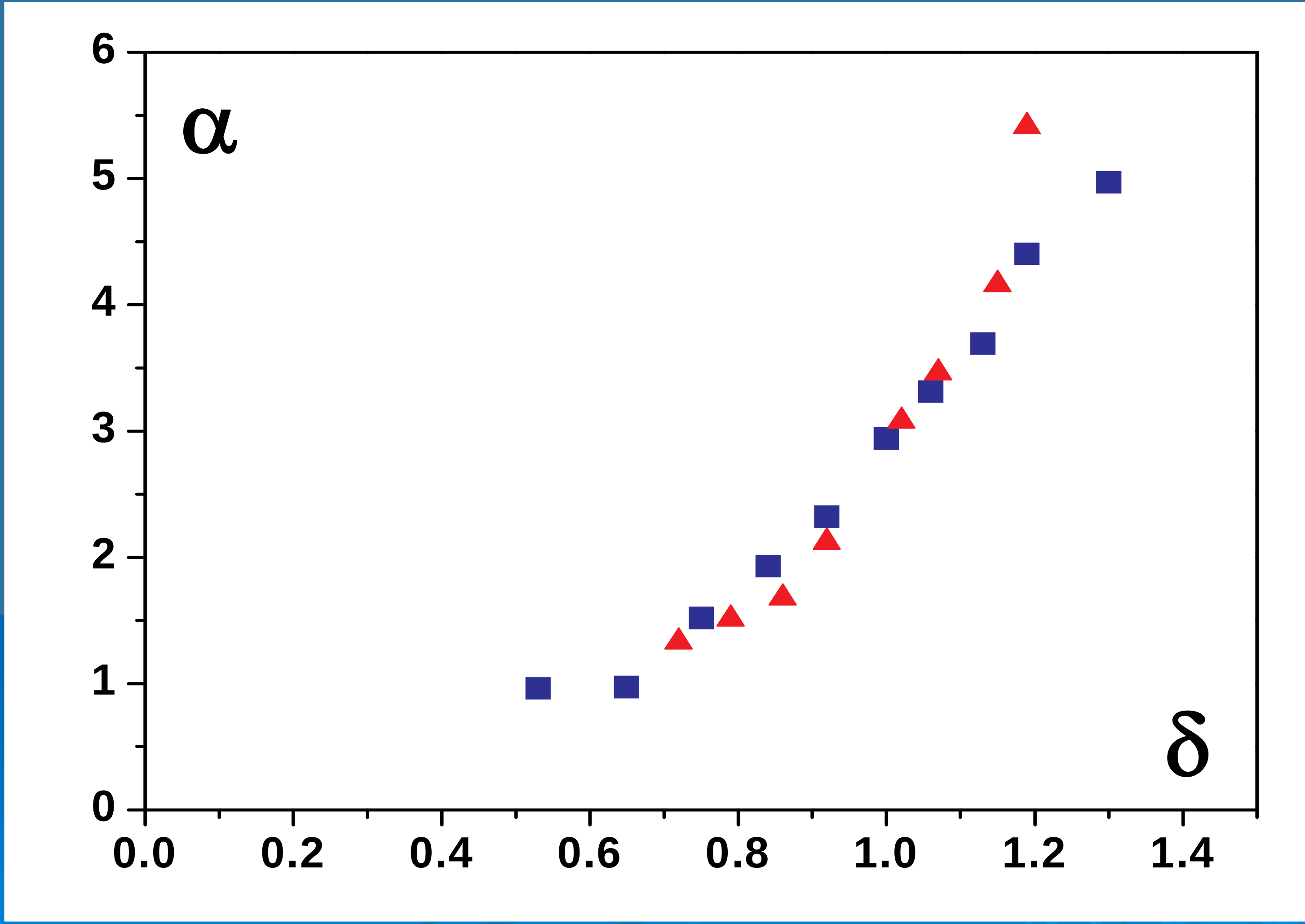
$$\mathbf{V}_\mathrm{eff} = -\mathrm{D_T}\ \alpha\ \frac{\vec{\nabla}\bar{T}}{\bar{T}}$$

Steady state:

$$\alpha = 1 + \frac{3}{Pe}\left(\frac{m_p}{m_\mu}\right)\left(\frac{\bar{T}}{T_*}\right)\ln\left(Re\right)$$

$$\bar{N}\,\bar{T}^{\alpha} = const$$

Coefficient α vs. Dimensionless Particle Size



■ - stable stratification, ▲ - unstable stratification.

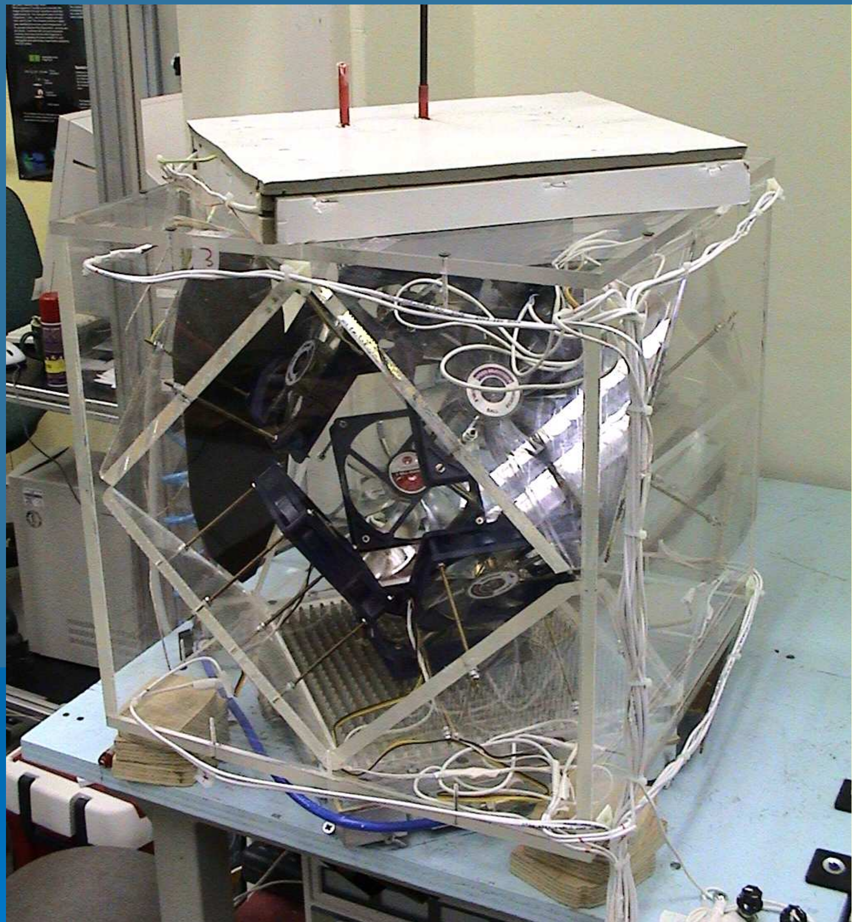
Parameters of turbulence and the turbulent thermal diffusion coefficient for stable stratification

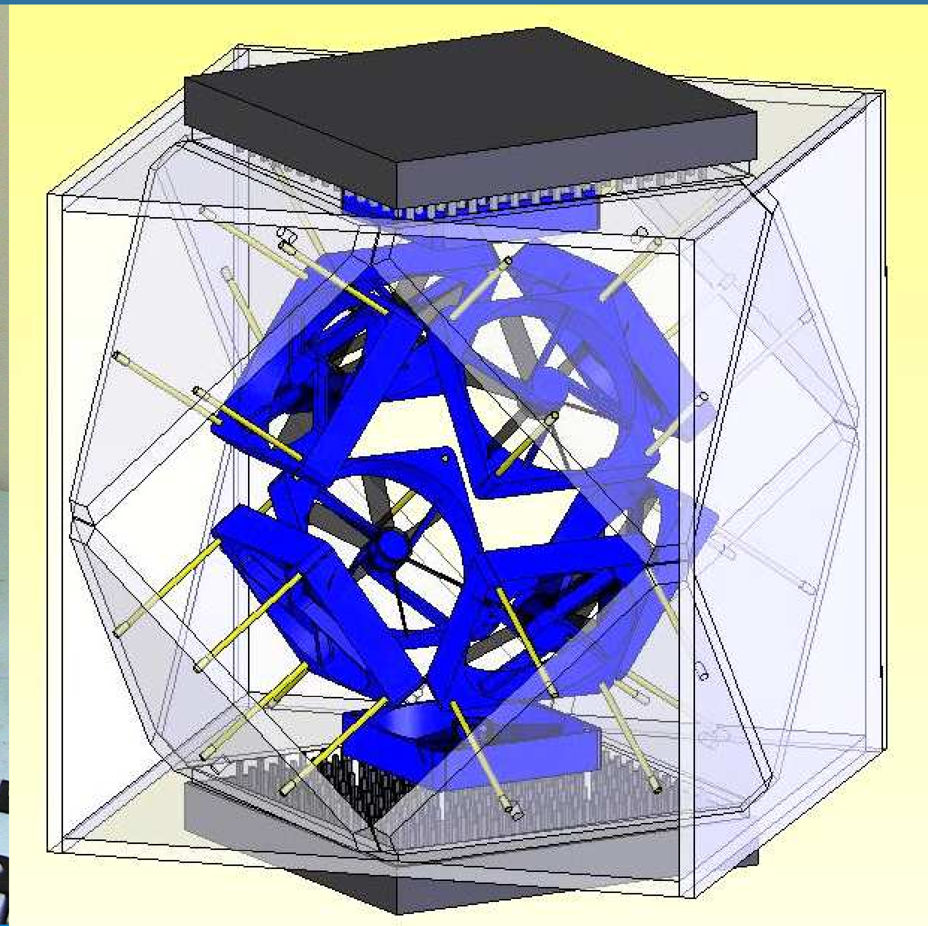
f (Hz)	$\sqrt{\langle u^2 \rangle}$ (cm/s)	*L* (cm)	Re	*α*
6.5	3.6	1.9	46	1.79
10.5	7.2	2.1	101	1.65
14.5	10.7	2.3	164	1.43
16.5	12.4	2.0	165	1.33

Parameters of turbulence and the turbulent thermal diffusion coefficient for unstable stratification

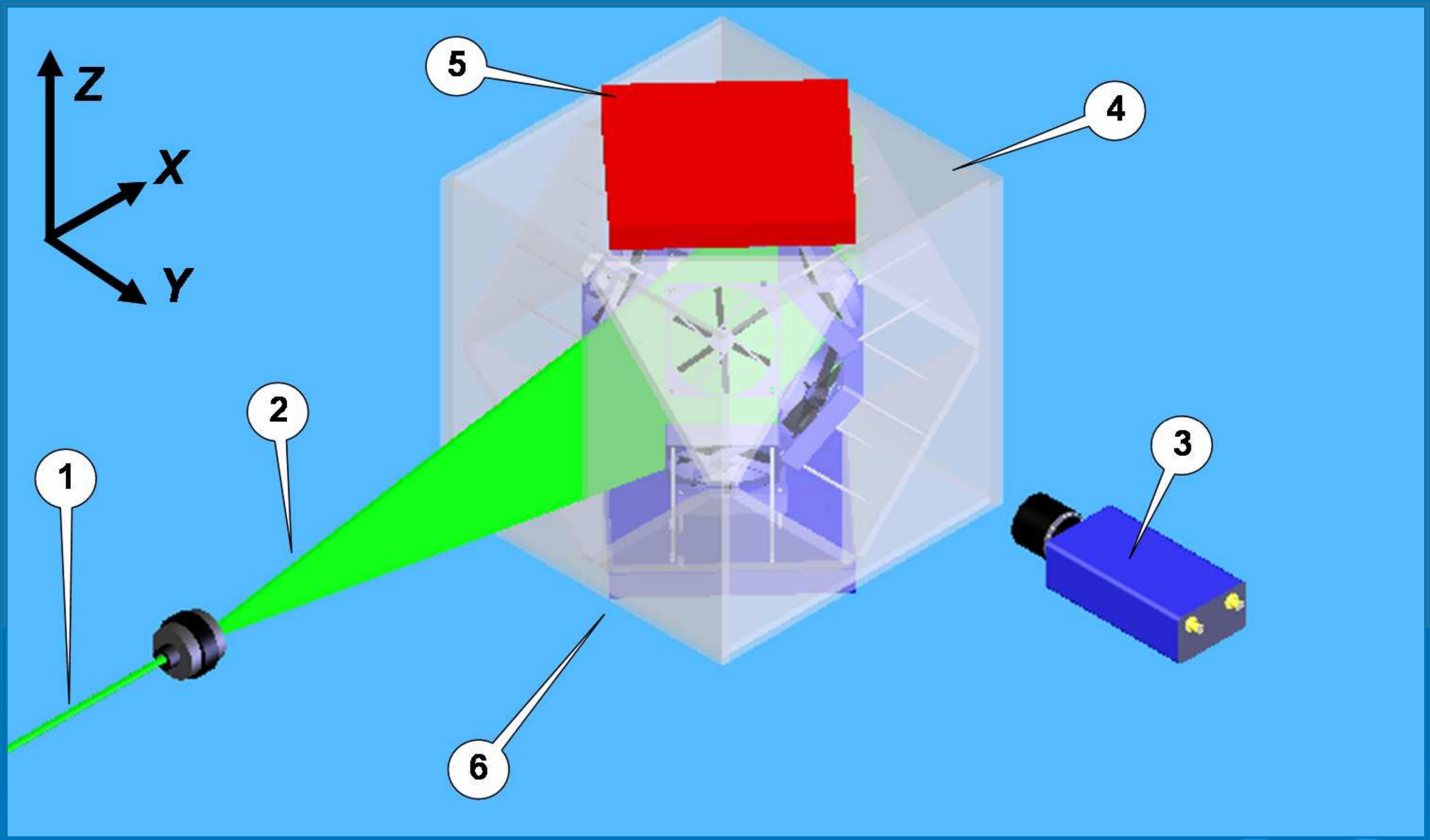
f (Hz)	$\sqrt{\langle u^2 \rangle}$ (cm/s)	*L* (cm)	Re	*α*
8.4	8.8	1.85	109	1.87
10.4	9.7	1.75	113	1.59
14.4	11.7	1.84	143	1.34
16.4	14.0	1.64	153	1.29

Experimental set–up with ten fans



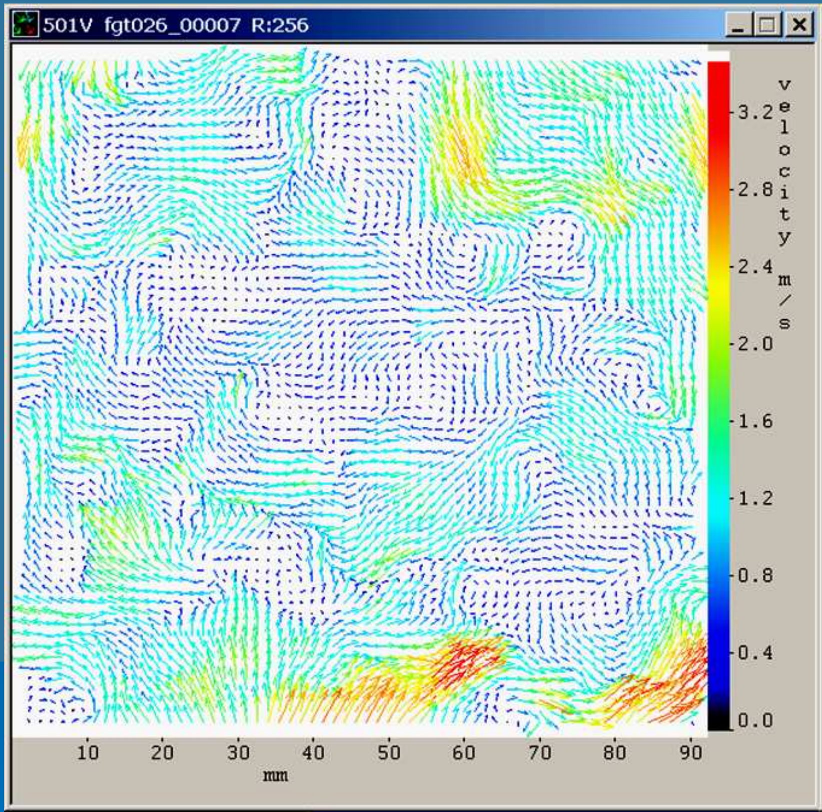


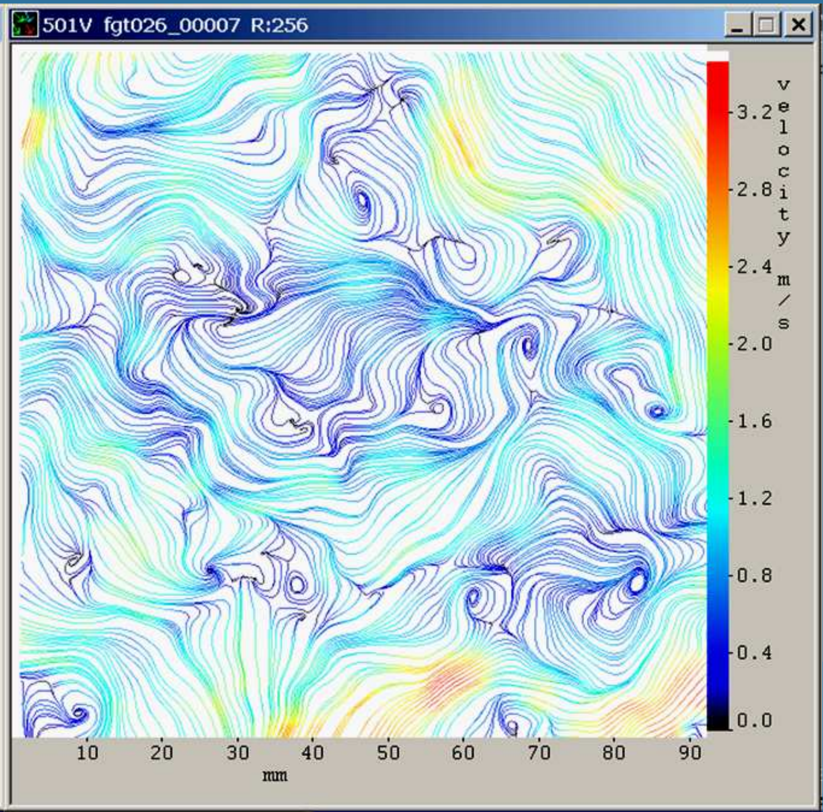
Experimental Set–up



1- laser beam, 2- light sheet, 3- CCD camera, 4- test section, 5- hot heat exchanger, 6- cold heat exchanger

Instantaneous vector map and streamlines of flow in FTG

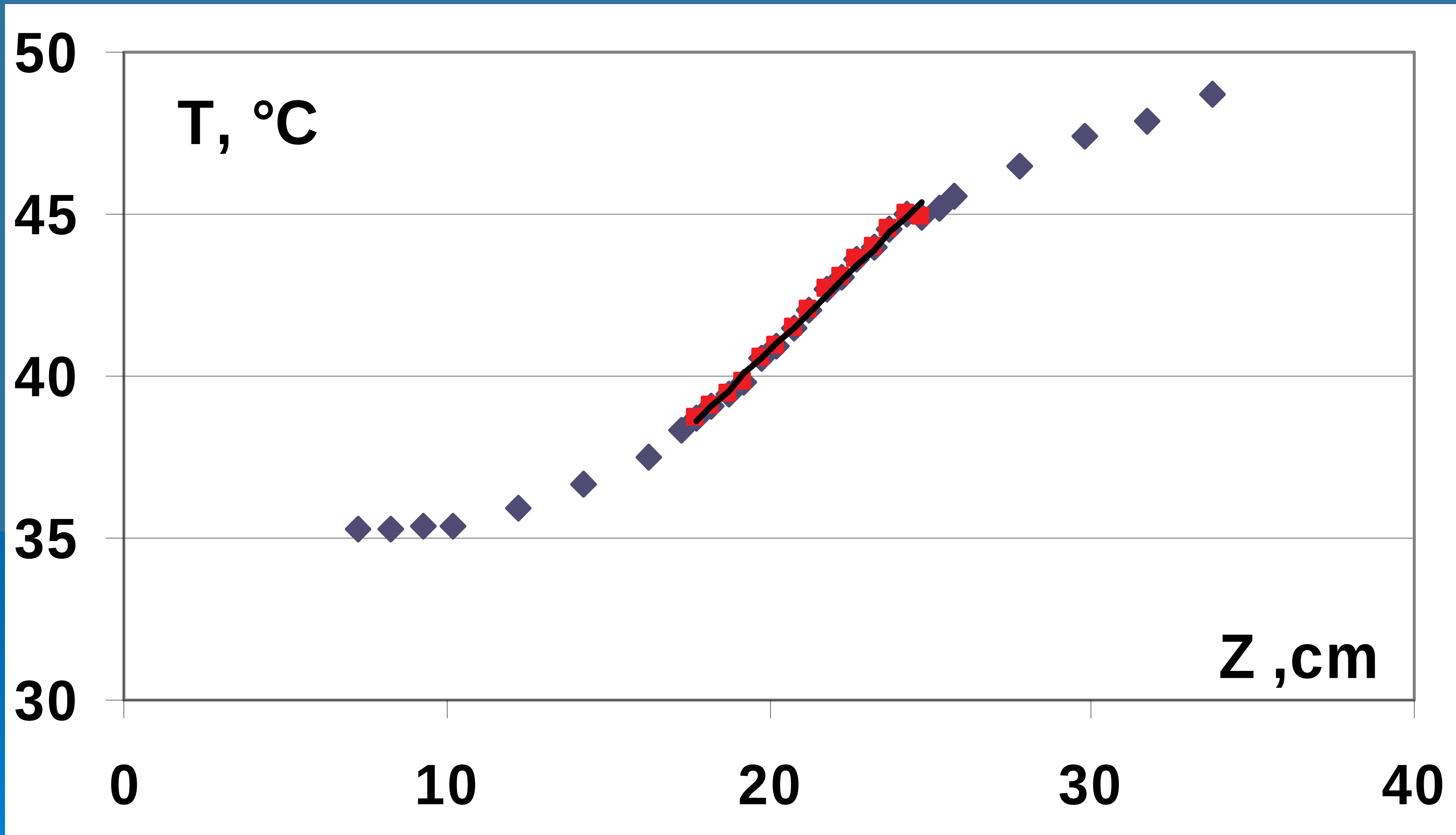




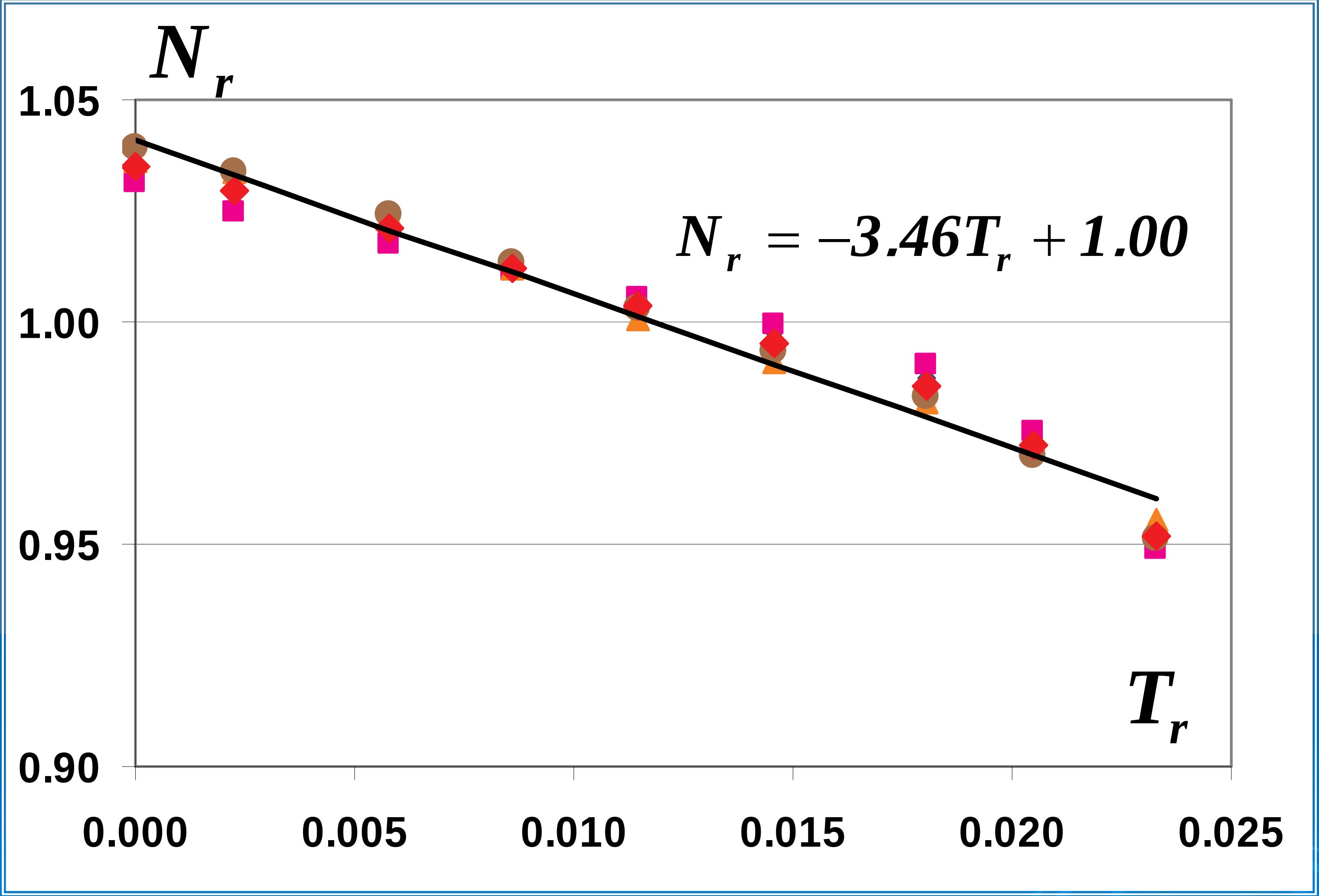
Characteristics of turbulence generated by ten fans

Setup number	FTG
$Re = uL/\nu$	644
Integral scale, L (cm)	1.2
R.m.s. velocity, u (cm/s)	105
Taylor scale, γ (cm)	0.161
Kolmogorov scale, η (mm)	0.096
Turnover time, t ms	11.5
Rate of dissipation, ε (cm^2/s^3)	$0.96 \cdot 10^6$

Mean temperature distribution in FGT

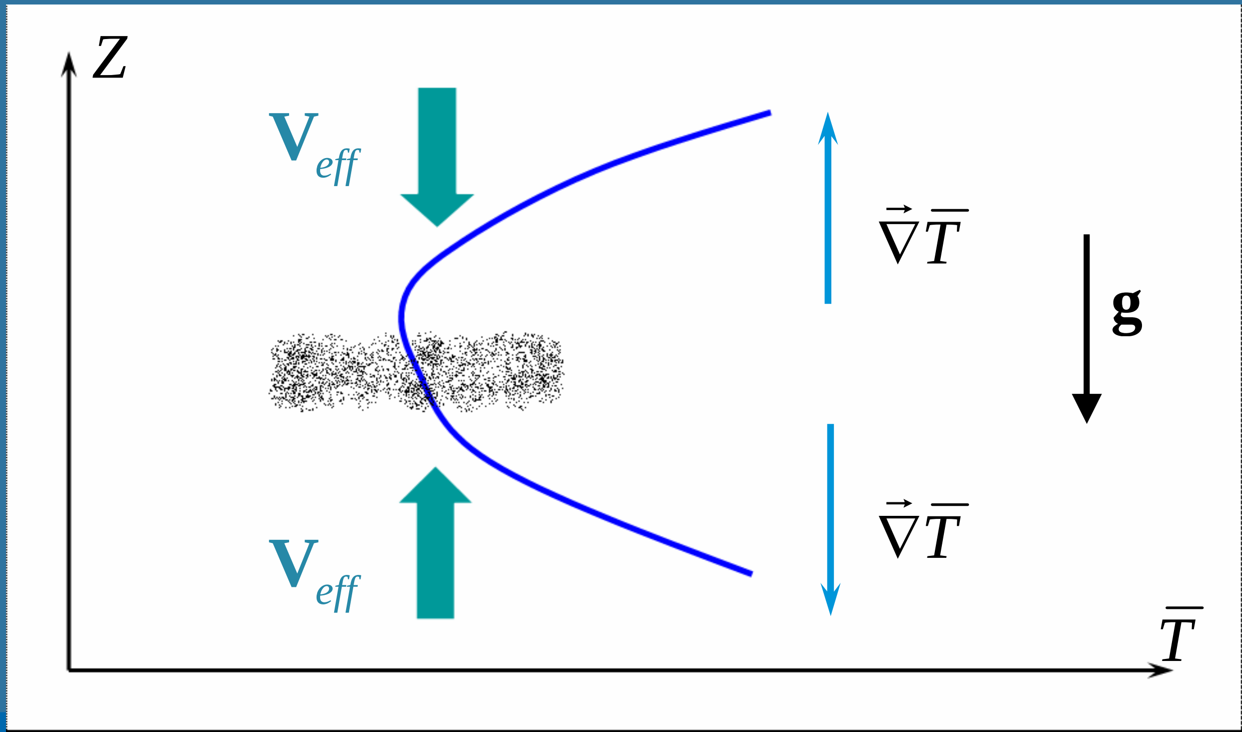


Turbulent Thermal Diffusion



Normalized mean particle number density $N_r = \overline{N}/\overline{N}_0$ vs. normalized temperature gradient $T_r = \left(\overline{T}\text{-}\overline{T}_0\right)/\overline{T}_0$ in FGT.

Turbulent Thermal Diffusion



$$\mathbf{V}_p = \overline{\mathbf{V}} + \mathbf{g}\,\tau_p + \mathbf{V}_{eff}$$

$$\mathbf{V}_{eff} \propto -\frac{1}{\mathrm{Pe}}\frac{m_p}{m_\mu}\ln \mathrm{Re}\,\frac{\vec{\nabla}\overline{T}}{\overline{T}_*}$$

The ratio $\left|\mathbf{V}_{eff}/W\right|$ for typical atmospheric parameters (different temperature gradients and different particle sizes)

a_*	1 K / 100 m	1 K / 200 m	1 K / 300 m
1 μm	13	6.5	4.33
5 μm	3.4	1.7	1.13
10 – 20 μm	3	1.5	1
30 μm	2.7	1.35	0.9

Ratio $\left|\mathbf{V}_{eff}/W\right|$ for Typical Atmospheric Parameters

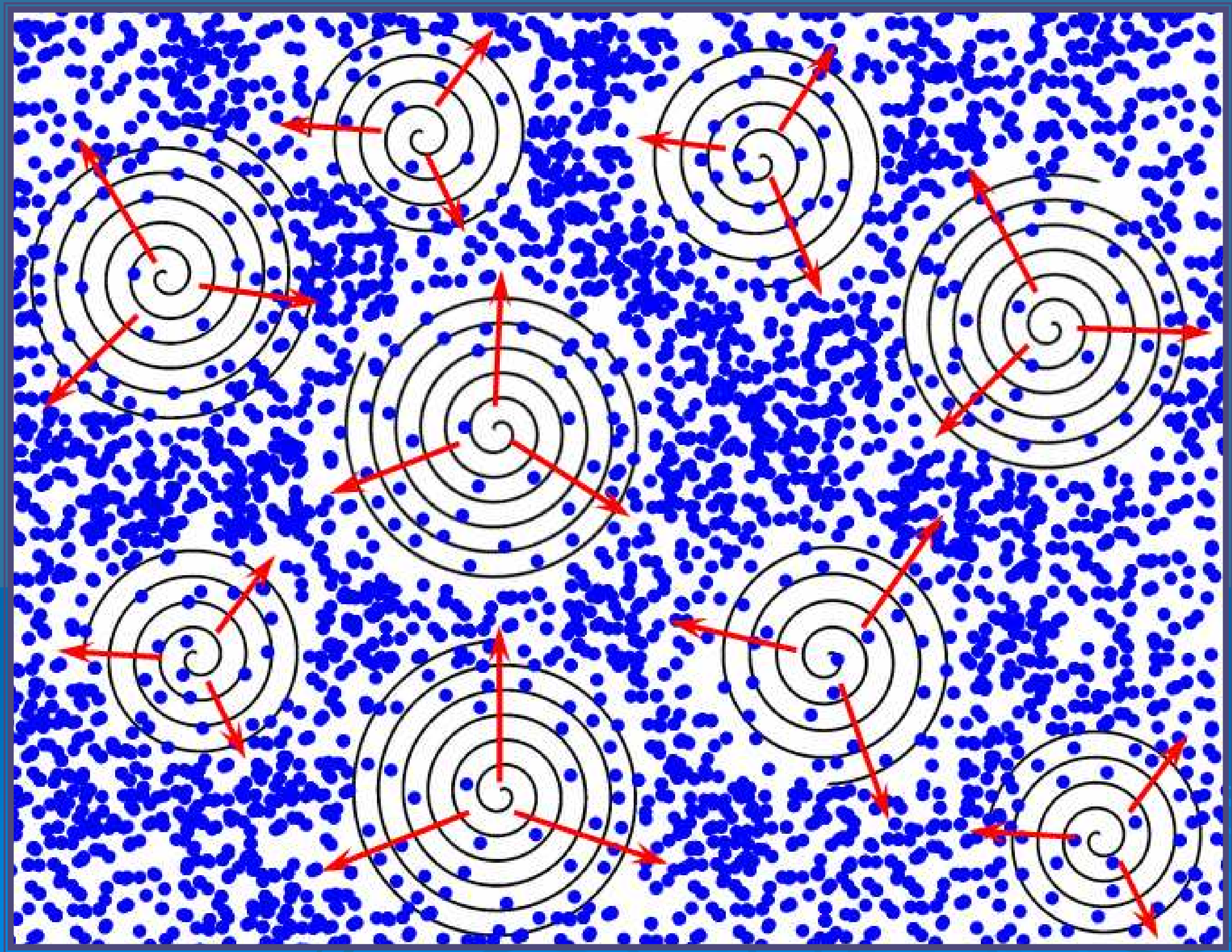
	1 K/100 m	1 K/200 m	1 K/300 m	1 K/1000 m
$a_* = 30\ \mu m$	2.7	1.35	0.9	0.27
$a_* = 50\ \mu m$	2.43	1.22	0.81	0.243
$a_* = 100\ \mu m$	2.06	1.03	0.687	0.206
$a_* = 200\ \mu m$	1.7	0.85	0.567	0.17
$a_* = 300\ \mu m$	1.5	0.75	0.5	0.15
$a_* = 500\ \mu m$	1.2	0.6	0.4	0.12

Time of Formation of Aerosol Layers

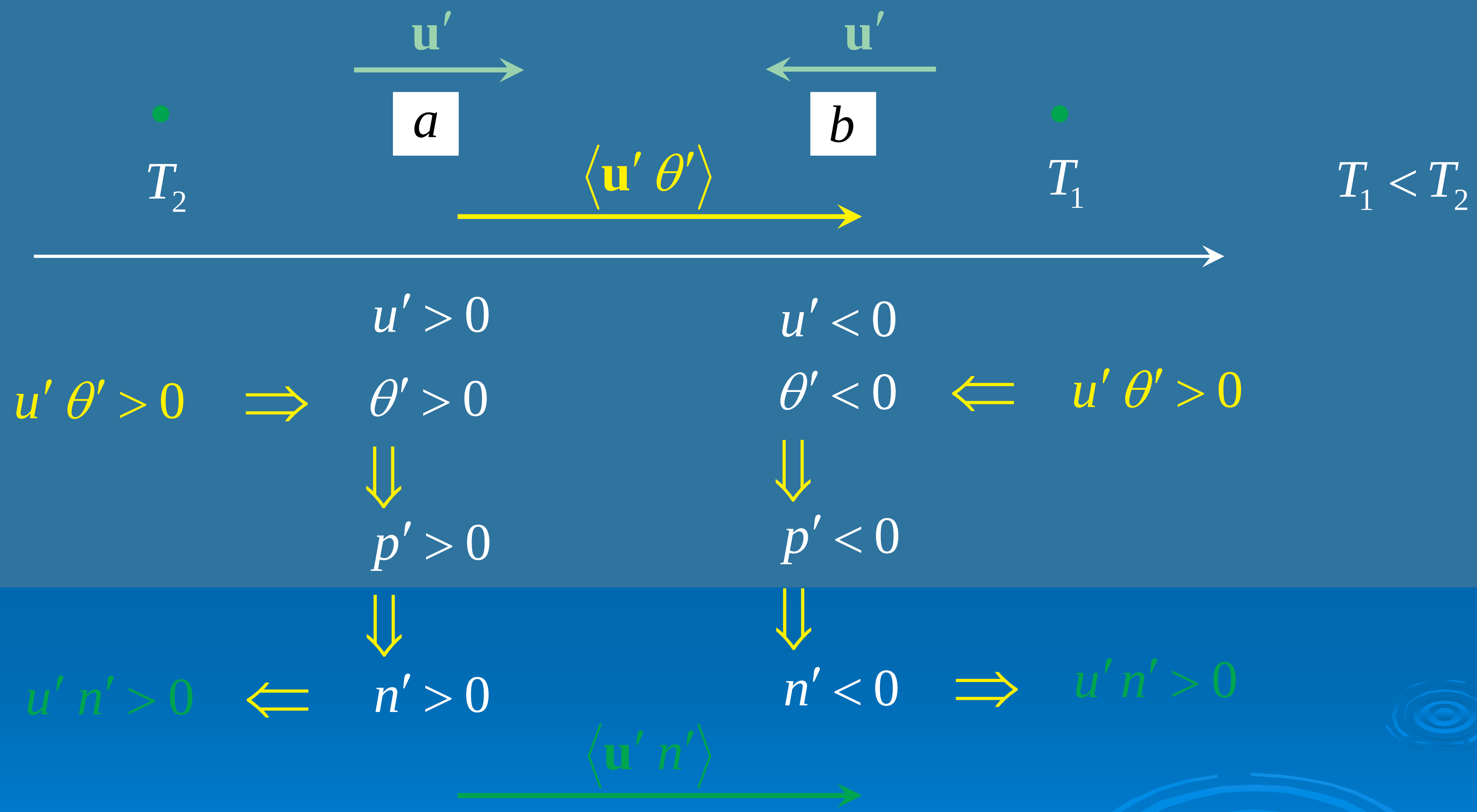
	1 K/100 m	1 K/200 m
$a_* = 30\ \mu m$	11 min	105 min
$a_* = 100\ \mu m$	1 min	120 min

$$t \propto \frac{L_T}{\left|\mathbf{V}_{eff} - \mathbf{W}\right|}$$

Particle Inertia Effect



Turbulent Thermal Diffusion



Non-diffusive mean flux of particles is in the direction of the mean heat flux (i.e., in the direction of minimum fluid temperature).

Paradox

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho\,\mathbf{u}) = 0 \qquad (1)$$

$$\frac{\partial n}{\partial t} + \mathrm{div}(n\,\mathbf{u}) = D\Delta\, n \qquad (2)$$

**Why does not turbulent diffusion arise in averaged equation (1) for a turbulent flow,
while averaged equation (2) does contain the turbulent diffusion?**

Paradox

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho\, \mathbf{u}) = 0 \qquad (1)$$

$$\frac{\partial n}{\partial t} + \operatorname{div}(n\, \mathbf{u}) = D \Delta n \qquad (2)$$

$$\frac{\partial \overline{N}}{\partial t} + \operatorname{div}\left(\overline{N}\, \overline{\mathbf{V}} + \overline{N}\, \overline{\mathbf{V}}_{eff} - D_T \nabla \overline{N}\right) = 0 \qquad \mathbf{V}_{eff} = D_T \frac{\nabla \overline{\rho}}{\overline{\rho}}$$

$$\frac{\partial \overline{N}}{\partial t} + \operatorname{div}\left(\overline{N}\, \overline{\mathbf{V}} + D_T \frac{\nabla \overline{\rho}}{\overline{\rho}} \overline{N} - D_T \nabla \overline{N}\right) = 0$$

$$\overline{N} = \overline{\rho} \quad \Rightarrow \quad \frac{\partial \overline{\rho}}{\partial t} + \operatorname{div}\left(\overline{\rho}\, \overline{\mathbf{V}} + D_T \frac{\nabla \overline{\rho}}{\overline{\rho}} \overline{\rho} - D_T \nabla \overline{\rho}\right) = 0$$

$$\frac{\partial \overline{\rho}}{\partial t} + \operatorname{div}\left(\overline{\rho}\, \overline{\mathbf{V}}\right) = 0$$

Phenomena

- Brownian diffusion – Einstein (1905);
  Smoluchowsky (1906)
- Thermophoresis – Tyndall (1870)
- Molecular thermal diffusion in gases – Enskog (1911);
  Chapman and Dootson (1917)
- Turbulent diffusion – Taylor (1921)
- Turbulent thermal diffusion of particles –
  Elperin, Kleeorin, Rogachevskii (1996)
- Turbulent thermal diffusion and turbulent barodiffusion in gases – Elperin, Kleeorin, Rogachevskii (1997)

References (Experimental study)

- A. Eidelman, T. Elperin, N. Kleeorin, A. Krein, I. Rogachevskii, J. Buchholz and G. Grünefeld. *Nonlinear Processes in Geophysics*, **11**, 343-350, 2004.

- J. Buchholz, A. Eidelman, T. Elperin, G. Grünefeld, N. Kleeorin, A. Krein and I. Rogachevskii. *Experiments in Fluids*, **36**, 879-887, 2004.

- A. Eidelman, T. Elperin, N. Kleeorin, I. Rogachevskii and I. Sapir-Katiraie. *Experiments in Fluids*, **40** , 744-752, 2006.

- A. Eidelman, T. Elperin, N. Kleeorin, A. Markovich, I. Rogachevskii. *Nonlinear Processes in Geophysics*, **13** , 109-117, 2006.

Inhomogeneous Structures

- Large-scale inhomogeneities

$$L_{LS} >> L$$

L is the maximum scale of turbulent motions

$L \approx 100$ m for atmospheric turbulence

- Small-scale inhomogeneities

$$L_{SS} << L$$

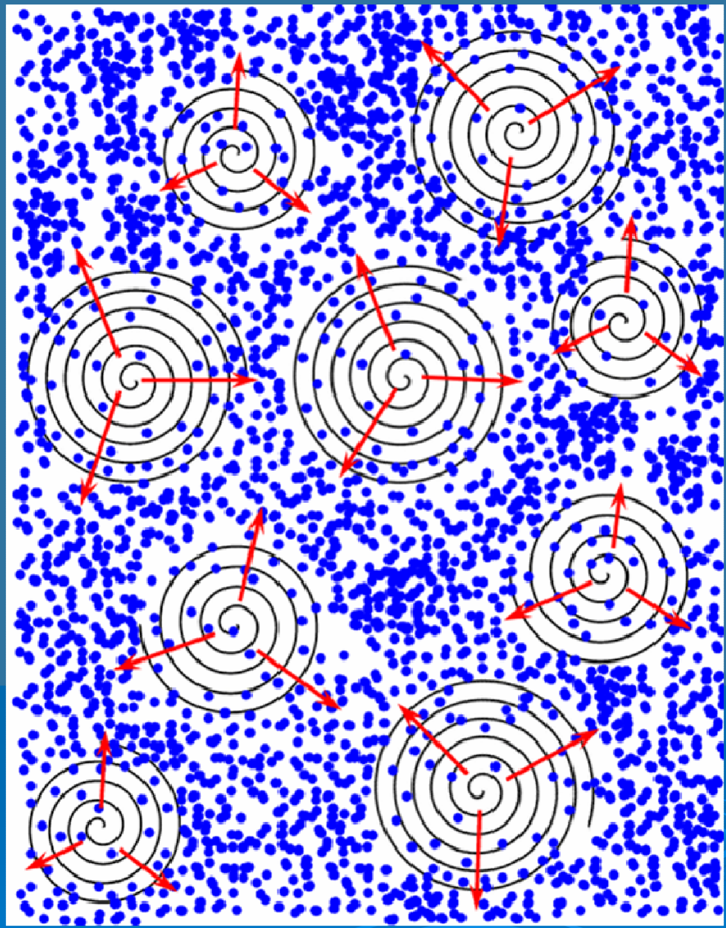
$L_{SS} < 1$ cm for atmospheric turbulence

Small-scale Inhomogeneities

- Inertia causes particles inside the turbulent eddies to drift out to the boundary regions between the eddies (i.e. regions with low vorticity or high strain rate and maximum of fluid pressure).
- This mechanism acts in a wide range of scales of turbulence.
- Scale-dependent turbulent diffusion causes relaxation of particle clusters.
- In small scales

$$D_T(l) \to D$$

- Thus, clusters of particles are localized in small scales.



Small-scale Inhomogeneities

$$\frac{\partial \Phi}{\partial t} = 2\Big(B(r) + 2\,\mathbf{U}(r)\cdot\nabla + \tilde{D}_{ij}\,\nabla_i\nabla_j \Big)\,\Phi(t,r)$$

$$\Phi(r) = \langle\, n'(\mathbf{x})\, n'(\mathbf{y}) \rangle \qquad r = |\,\mathbf{x} - \mathbf{y}\,|$$

$$B(r) = \tau \langle\, \mathrm{div}\,\mathbf{u}(\mathbf{x})\; \mathrm{div}\,\mathbf{u}(\mathbf{y}) \rangle$$

- source of particle fluctuations

$$\mathbf{D}_{ij} = \tau \langle\, u_i(\mathbf{x})\, u_j(\mathbf{y}) \rangle$$

- turbulent diffusion

$$\mathbf{U}(r) = \tau \langle\, \mathbf{u}(\mathbf{x})\; \mathrm{div}\; \mathbf{u}(\mathbf{y}) \rangle$$

- effective velocity

Clustering Instability

Mechanism of aerosol clustering instability is associated with exponential growth of the second moment of particle number density in turbulent flow.

The clustering instability is a combined effect of particle inertia and finite correlation time of the turbulent velocity field.

The instability criterion $$a > a_{critical} \cong 10 \div 20 \ \mu\text{m}$$

The growth rate $$\gamma \propto \tau_\eta^{-1} \left(\frac{a}{a_{critical}} \right)^4$$

For the atmospheric turbulence: $$\tau_\eta \approx 10^{-2} \div 10^{-1} \ \text{s}$$

The size of the clusters: $$\eta \approx 10^{-1} \ \text{cm}$$

Clustering Instability

The concentration of droplets in a cluster:

$$n_{cluster} \propto \frac{1}{a^3}\left(\frac{\eta}{a}\right)\frac{\rho}{3\rho_p} \approx 3\times10^5\,\mathrm{cm}^{-3}$$

The mean number density of droplets in clouds:

$$\overline{N} \approx 10^2 \div 10^3\,\mathrm{cm}^{-3} << n_{cluster}$$

The total number of particles inside the cluster ≈ 300

The clustering instability serves as a preliminary stage for a coagulation of water droplets leading to a rain formation.

References (Small-scale Effects)

T. Elperin, N. Kleeorin and I. Rogachevskii

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T. Elperin, N. Kleeorin, I. Rogachevskii and D. Sokoloff

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Environmental Fluid Mechanics **7**, 173–193 (2007)

Conclusion

Large-scale effects

- A new phenomenon of turbulent thermal diffusion associated with turbulent transport of particles in the atmosphere and in laboratory experiments was found.
- The essence of this phenomenon is the appearance of a nondiffusive mean flux of particles in the direction of the mean heat flux, which results in the formation of large-scale inhomogeneities in the spatial distribution of particles. Particles accumulate in regions of minimum mean temperature of the surrounding fluid.
- The effect of turbulent thermal diffusion was detected experimentally: in two oscillating grids turbulence generator and in a multi-fan turbulence generator in two directions of the imposed vertical mean temperature gradient (stable and unstable stratifications).
- Turbulent thermal diffusion can explain the large-scale aerosol layers that form inside atmospheric temperature inversions.

Conclusion

Small-scale effects

- A mechanism of formation of small-scale inhomogeneities in particles spatial distribution due to the clustering instability is found.

- The clustering instability is a combined effect of the particles inertia and a finite correlation time of the velocity field.

- The crucial parameter for the clustering instability is the size of the particles. The critical size of cloud droplets required for cluster formation is more than 20 μm.

- A mechanism of saturation of the clustering instability associated with the particles collisions in the clusters is suggested. We estimated a nonlinear level of the saturation of the droplets number density in clouds which exceeds by the orders of magnitude their mean number density.

- The clustering instability serves as a preliminary stage for a coagulation of water droplets leading to a rain formation.

THE END