Contributions of the direct numerical simulation method to the validation of statistical turbulence models for natural convection

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Introduction

- Passive decay heat removal in metal and water cooled reactors
  - experiments (scaled reactor models, water as model fluid)
  - engineering computer codes (e.g. FLUTAN)

- Validation of statistical turbulence models for natural convection in liquid metals
  - basic experiments in simple geometries
  - <u>direct numerical simulation</u>

Method of direct numerical simulation

- Conservation equations of mass, momentum and energy

$$\nabla \vec{u} = 0$$

$$\partial \vec{u} / \partial t + (\vec{u} \nabla) \vec{u} = - \nabla p + \frac{1}{\sqrt{Gr}} \nabla^2 \vec{u} + \left(T_{ref} - T \right) \frac{\vec{g}}{|\vec{g}|}$$

$$\partial T / \partial t + (\vec{u} \nabla) T = \frac{1}{Pr \sqrt{Gr}} \nabla^2 T$$

- 3d, time dependent
- resolve all spatial scales of turbulence

→ + no model assumptions, no parameters

– limited to small turbulence levels and simple geometries

Computer code TURBIT

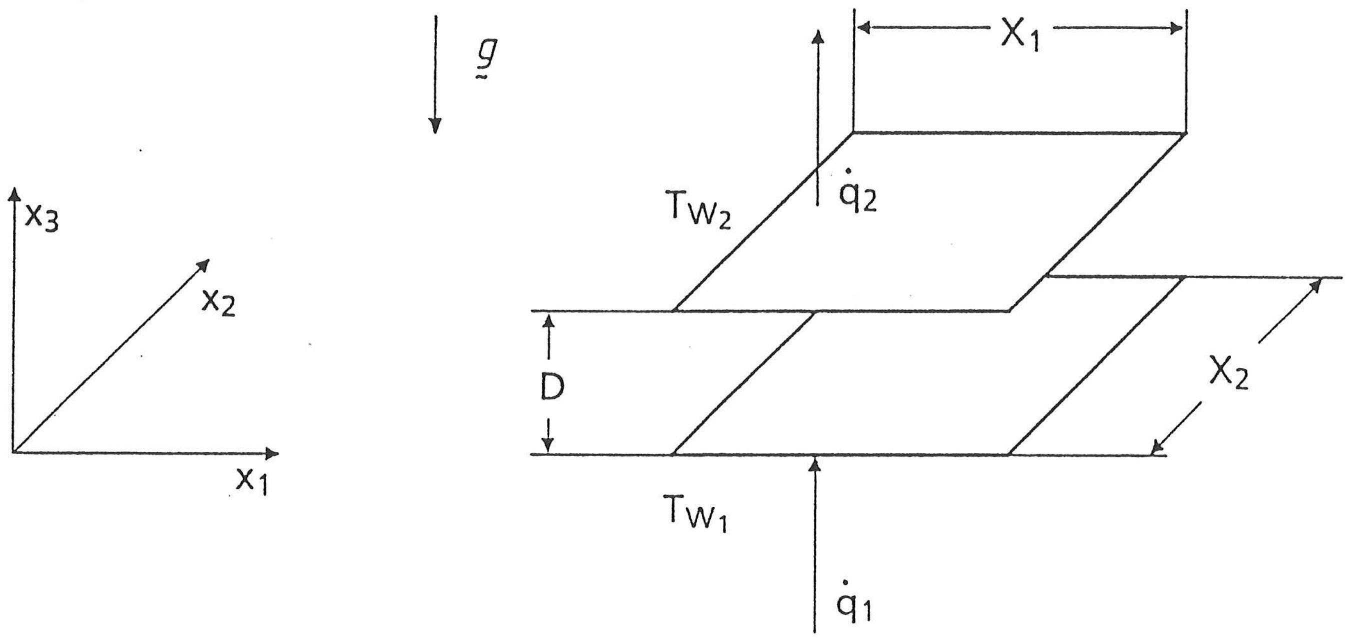
- finite volume method
  - central finite differences
  - staggered grid

- time integration
  - momentum equation: explicit
  - energy equation: explicit or semi-implicit
  - Poisson equation for pressure

- geometry
  - plane channel
  - annulus

Rayleigh-Bénard convection

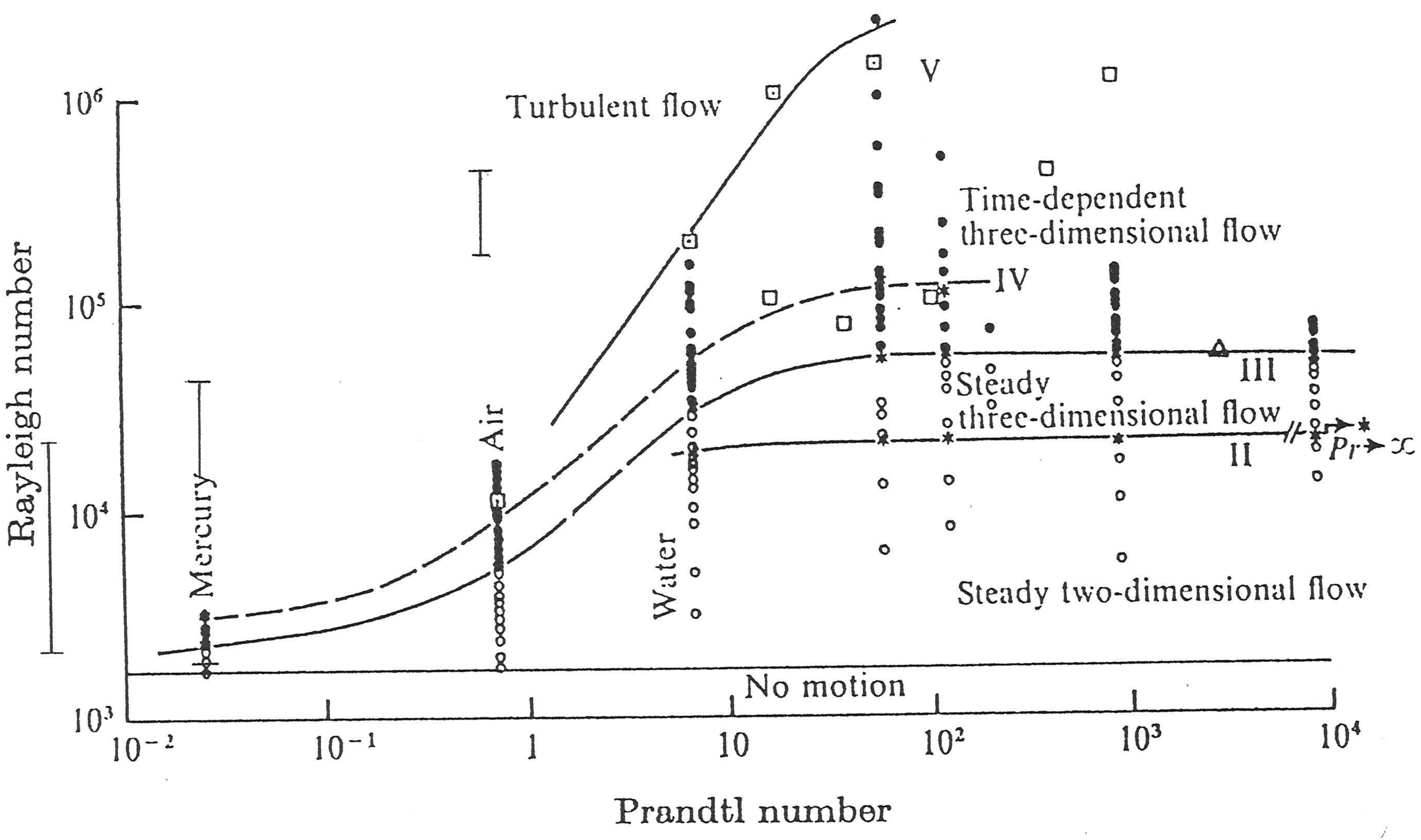
- geometry



- dimensionless numbers
  - Rayleigh number $Ra \sim \Delta T_w$
  - Prandtl number $Pr = \nu/\kappa$

sodium:	$Pr = 0.006$
mercury:	$Pr = 0.024$
air:	$Pr = 0.71$

Rayleigh-Bénard convection



Statistical Turbulence Models

- closure of $-\overline{u_i'u_j'}$, $-\overline{u_i'T'}$
  - solution of modelled transport equations for turbulent quantities
    e.g.: k, ε, $\overline{T'^2}$, ε_T, $-\overline{u_i'u_j'}$, $-\overline{u_i'T'}$

- use DNS-data to
  - analyse exact transport equations for k, ε, ...
  - analyse model assumption for different terms

Transport equation for turbulent heat flux $\overline{u_3'T'}$

$$0 = -\frac{\partial}{\partial x_3}\left(\overline{u_3'^2 T'} + \overline{p'T'} - \frac{1}{Pr\sqrt{Gr}}\,\overline{u_3'\frac{\partial T'}{\partial x_3}} - \frac{1}{\sqrt{Gr}}\,\overline{T'\frac{\partial u_3'}{\partial x_3}} \right)$$

D_q

$$- \overline{u_3'^2}\,\frac{\partial \overline{T}}{\partial x_3} + \overline{T'^2} \qquad + \overline{p'\frac{\partial T'}{\partial x_3}}$$

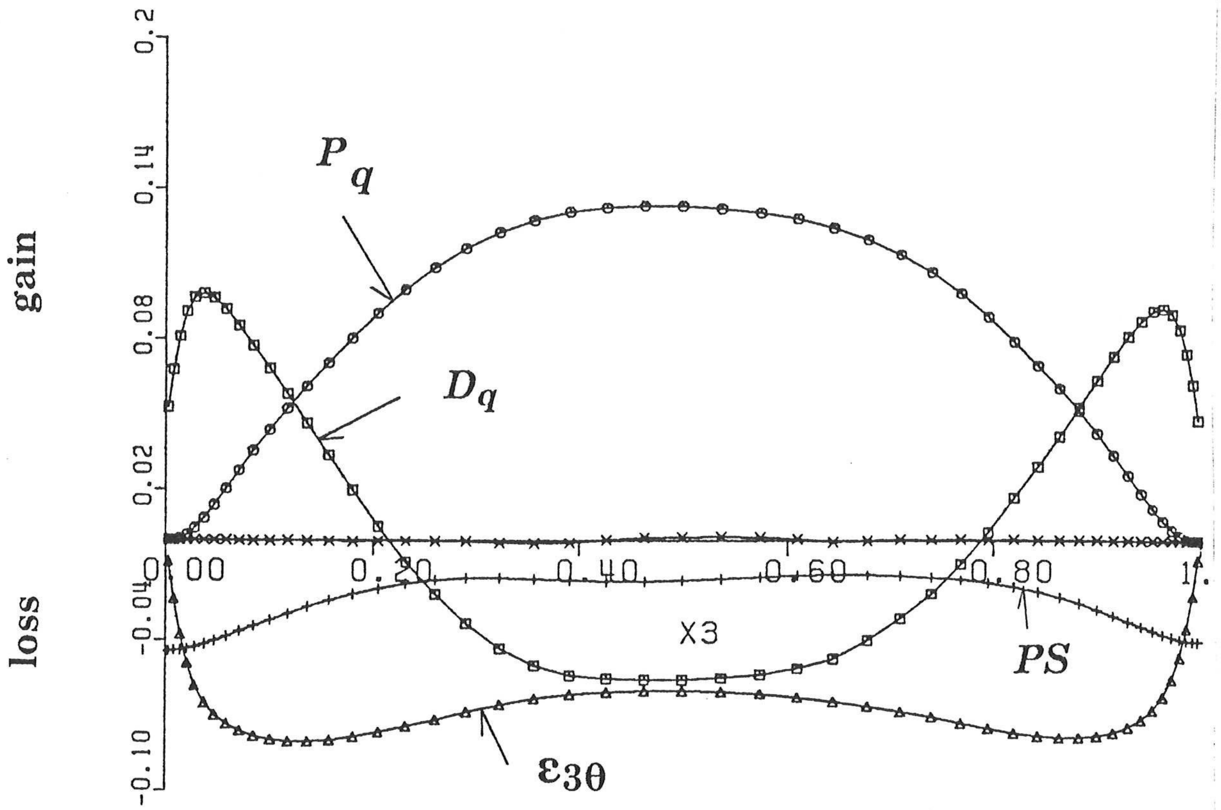
P_q $\qquad$ PS

$$- \frac{1}{\sqrt{Gr}}\left(1 + \frac{1}{Pr}\right)\overline{\frac{\partial u_3'}{\partial x_i}\cdot\frac{\partial T'}{\partial x_i}}$$

$\varepsilon_{3\theta}$

Budget of $\overline{u_3'T'}$

- **Sodium, $Ra = 24\,000$**

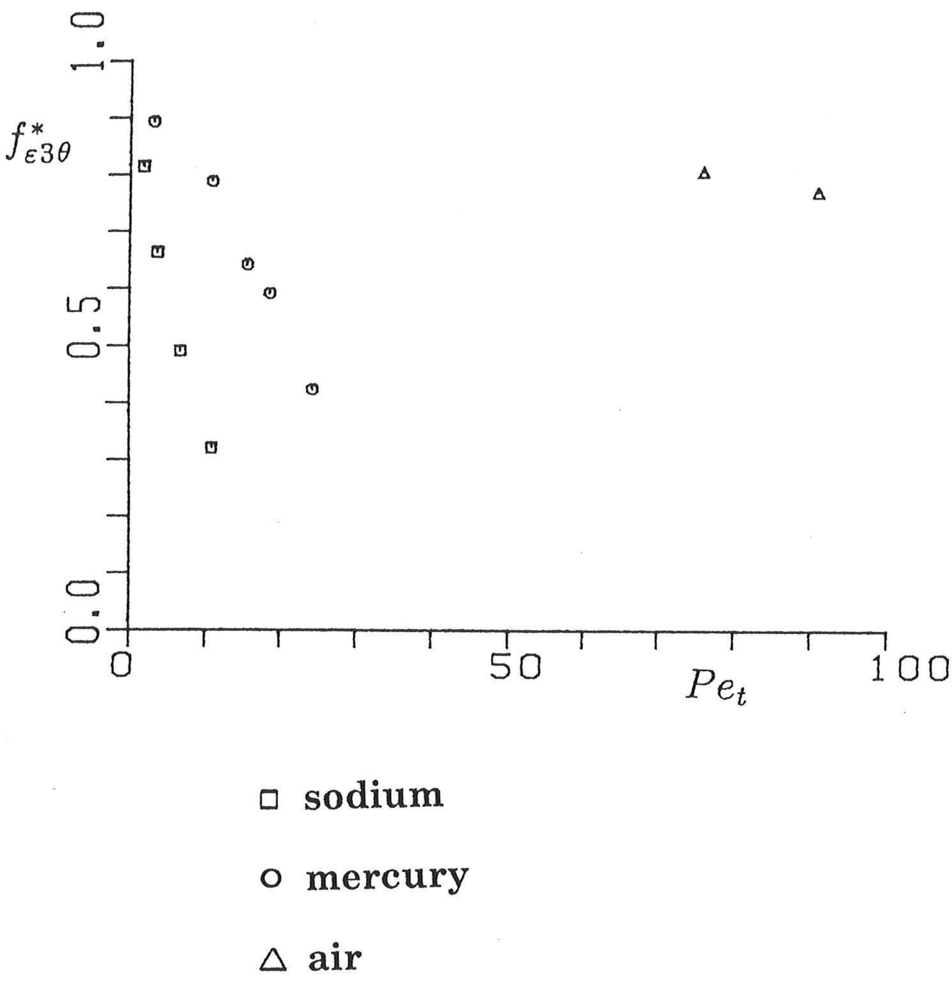


Modelling of $\varepsilon_{i\theta}$

- Shikazono & Kasagi (1993):

$$\varepsilon_{i\theta} = f^{*}_{\varepsilon i\theta} \frac{1+Pr}{2\sqrt{Pr}\sqrt{R}} \frac{\varepsilon}{k} \overline{u_i'T'}$$

- Analysis of $f^{*}_{\varepsilon 3\theta}$ by DNS-data



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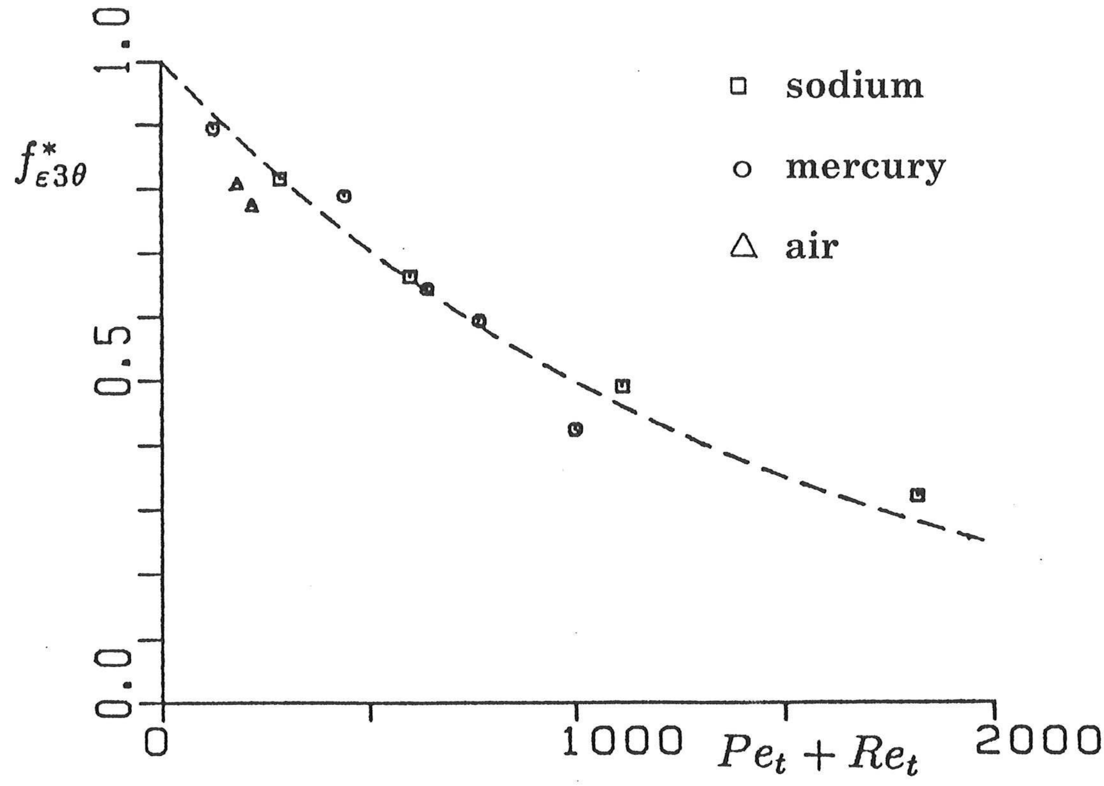
- **Analysis of $f^{*}_{\varepsilon 3\theta}$ by DNS-data**



$$f^{*}_{\varepsilon i\theta} = exp\left(-C_{\varepsilon i\theta}\left(Re_t + Pe_t\right)\right)$$

$$C_{\varepsilon 3\theta} \approx 0.0007$$

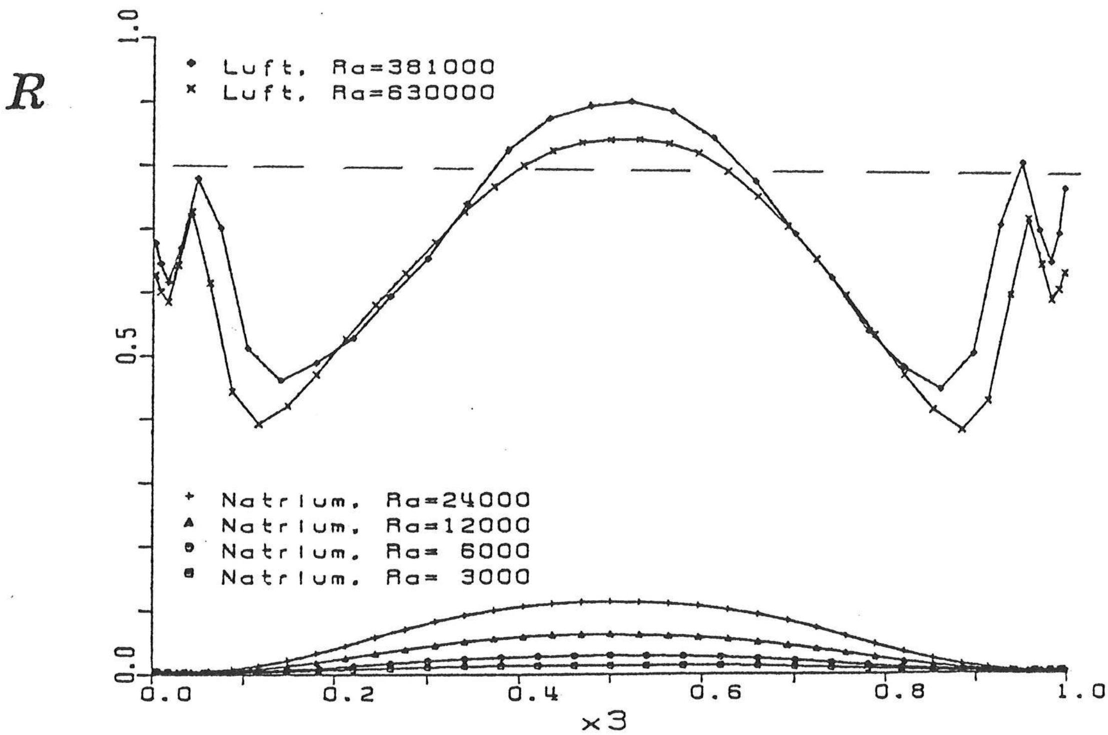
Closure of sink term ε_T

- Launder (1975)

$$\varepsilon_T = \frac{1}{R} \frac{\overline{T'^2}/2}{k} \varepsilon$$

$$R \approx 0.8$$

- evaluation of R



Conclusions

- **Direct numerical simulation**
  - no assumptions about turbulence
  - numerical experiment
  - simple geometries
  - small turbulence levels

  here: Rayleigh-Bénard convection, three fluids

- **Validation of statistical turbulence models**
  - evaluation of all correlations
  - analysis of budgets of turbulent quantities
  - analysis of model assumptions
  - calibration of coefficients and improvement of models