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Turbulent heat flux balance for natural convection in air and sodium analysed by direct numerical simulations

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Introduction

- **Motivation**

  turbulent heat transfer in buoyant flows

  k-ε turbulence model

$$\overline{u_i'T'} = -\kappa_t \frac{\partial \overline{T}}{\partial x_i}, \quad \kappa_t = \frac{\nu_t}{Pr_t}$$

  - inadequate for buoyant flows

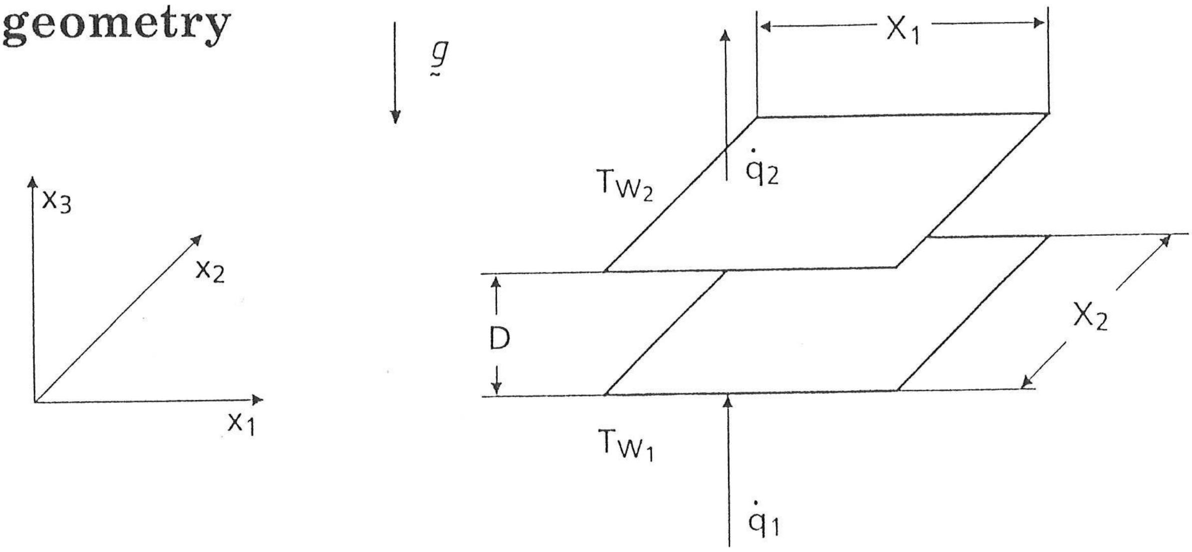
  full differential models for $\overline{u_i'T'}$

  - closure of unknown correlations

- **Objective**
  - detailed analysis of all terms in $\overline{u_i'T'}$-equation
  - turbulent natural convection in sodium and air
  - evaluation of direct simulation results

Rayleigh-Bénard convection

- geometry



- dimensionless numbers

  - Rayleigh-number:

$$Ra = \frac{g\beta\left(T_{W1} - T_{W2}\right) D^3}{\nu \kappa}$$

  - Prandtl-number: $Pr = \nu/\kappa$

    air: $Pr = 0.71$, sodium: $Pr = 0.006$

  - Grashof number: $Gr = Ra/Pr$

Direct simulation method

- full conservation equations for
  - mass
  - momentum
  - energy

- three-dimensional, time-dependent

- resolve all scales

→ no model assumptions
no parameters

Computer code TURBIT

- finite volume method

- spatial discretization
  - finite differences
  - staggered grid

- time integration
  - momentum equation

    explicit Euler Leapfrog scheme
    projection method of Chorin

  - thermal energy equation

    semi-implicit Leapfrog-Crank-Nicholson scheme

- verified for natural and forced convection in various fluids

Case specifications

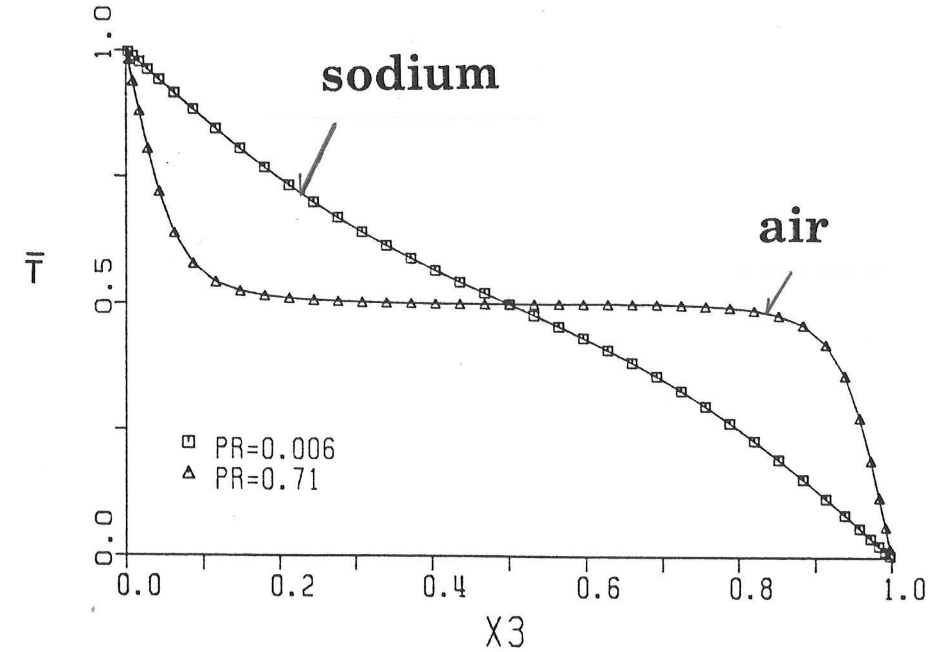
Fluid	Ra	Gr	grid
air	630,000	$0.9 \cdot 10^6$	$200 \cdot 200 \cdot 39$
sodium	24,000	$4 \cdot 10^6$	$250 \cdot 250 \cdot 39$

- boundary conditions:
  - periodic in horizontal direction ($X_{1,2} = 8$)
  - walls: no slip condition
    constant wall temperatures

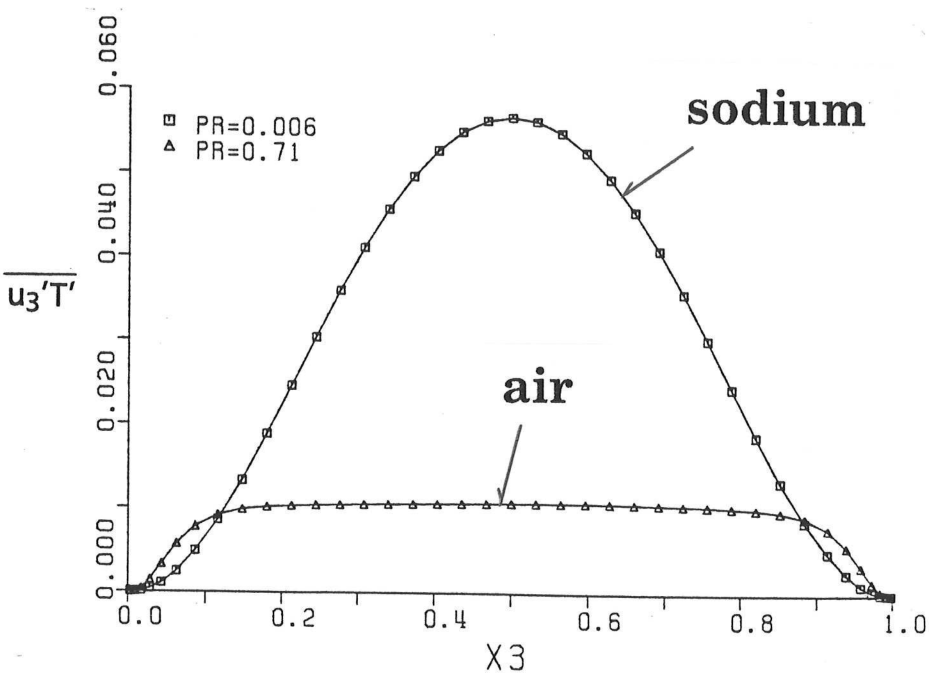
- initial conditions
  - final data of air / sodium simulations
    with lower Ra

Evaluated results

- **mean temperature**



- **vertical turbulent heat flux**



Transport equation for $\overline{u_3'T'}$

- turbulent Rayleigh-Bénard convection
  - no mean velocity $\overline{u_i} = 0$
  - no gradients in horizontal directions

$$0 = \underbrace{-\overline{u_3'^2}\,\frac{\partial \overline{T}}{\partial x_3} + \overline{T'^2}}_{P}$$

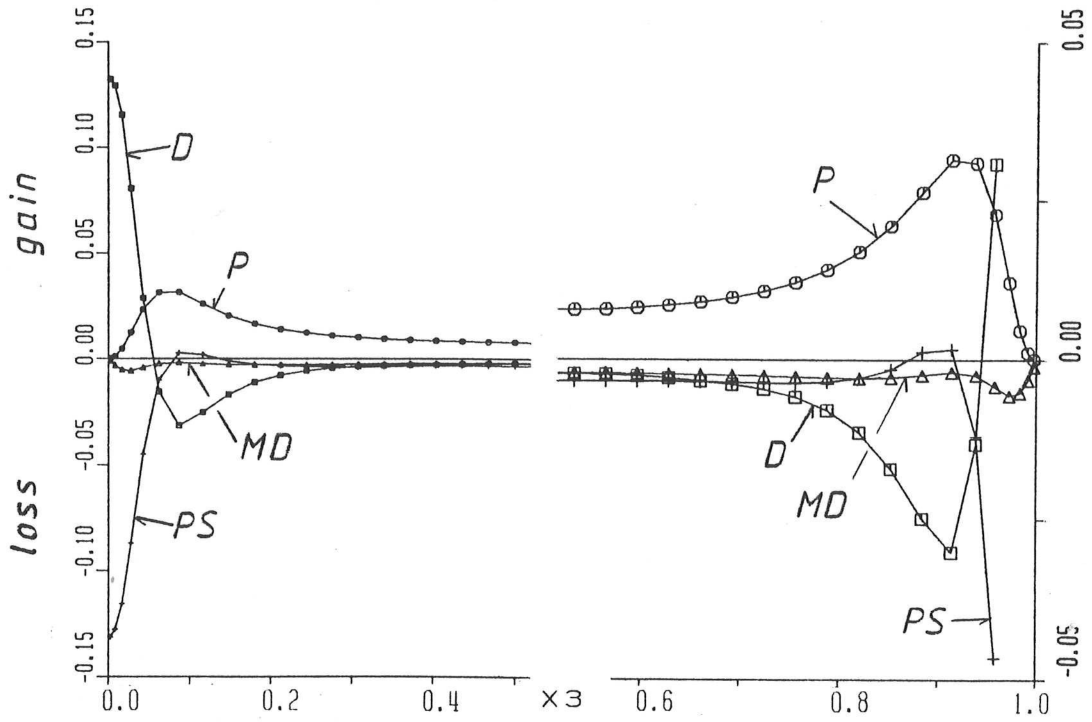
$$\underbrace{-\frac{\partial}{\partial x_3}\left(\overline{u_3'^2 T'} + \overline{p'T'} - \frac{1}{Pr\sqrt{Gr}}\,\overline{u_3'\frac{\partial T'}{\partial x_3}} - \frac{1}{\sqrt{Gr}}\,\overline{T'\frac{\partial u_3'}{\partial x_3}}\right)}_{D}$$

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

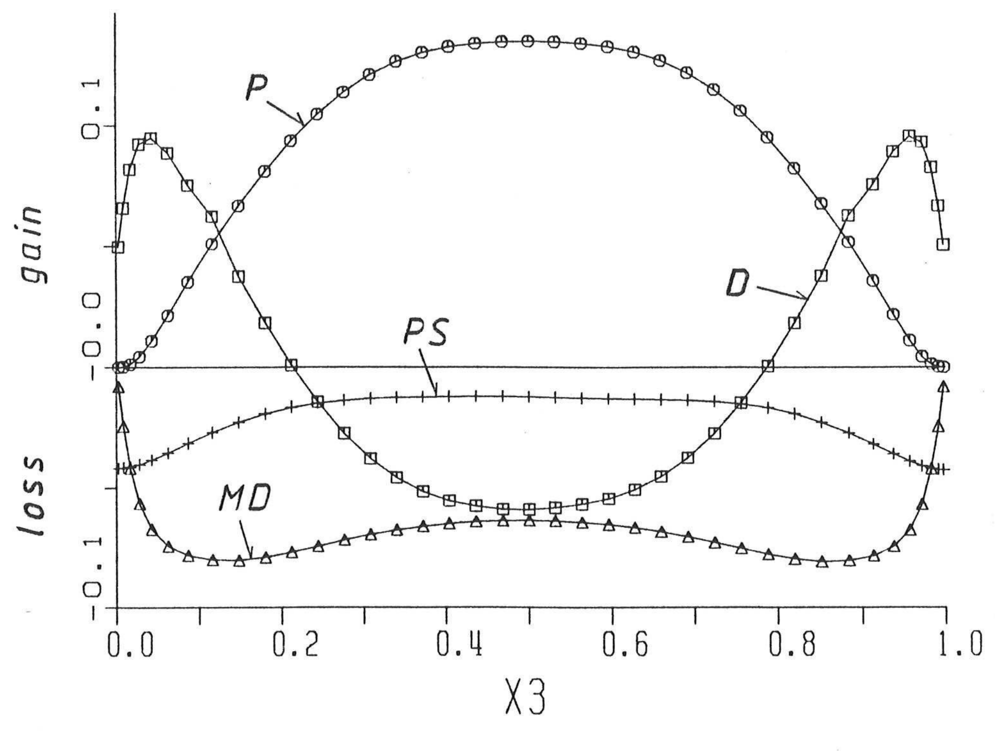
$$\underbrace{+\overline{p'\frac{\partial T'}{\partial x_3}}}_{PS}$$

Turbulent heat flux budget

- **air (Pr = 0.71)**



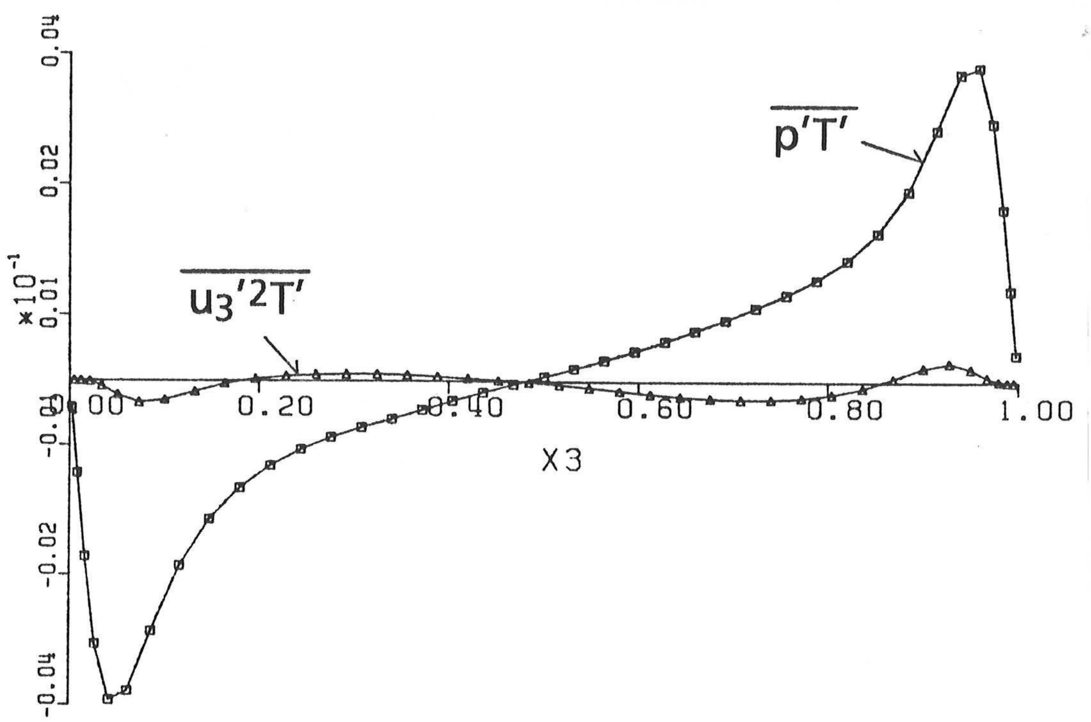
- **sodium (Pr = 0.006)**



Analysis of diffusion of $\overline{u_3'T'}$

$$\underbrace{-\frac{\partial}{\partial x_3}\left(\overline{u_3'^2 T'} + \overline{p'T'} - \frac{1}{Pr\sqrt{Gr}}\overline{u_3'\frac{\partial T'}{\partial x_3}} - \frac{1}{\sqrt{Gr}}\overline{T'\frac{\partial u_3'}{\partial x_3}}\right)}_{\mathbf{D}}$$

- **air**



Conclusions

- **Direct numerical simulation**
  - turbulent Rayleigh-Bénard convection
  - air and sodium

- **Balance of vertical turbulent heat flux**
  - no local equilibrium $P \neq PS$
  - molecular destruction is important sink
  - redistribution of $\overline{u_3'T'}$ by diffusion
  - turbulent diffusion mainly due to $\overline{p'T'}$

- **Standard turbulence models**
  - neglect pressure diffusion
  - neglect molecular destruction