2003 Robert Henry Thurston Lecture

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Carl T. Herakovich

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Vice President
Basic Engineering

2003 ASME IMECE
November 19, 2003, Washington, D. C.

ROBERT HENRY THURSTON LECTURE

- Established in 1925
- Honors Robert Henry Thurston the first president of ASME and a farseeing leader in science and engineering
- Lecture encourages stimulating thinking on a subject of broad technical interest to engineers

2003 ASME Thurston Lecture
November 19, 2003, Washington, D. C.

YOGESH JALURIA

Board of Governors Professor
Department of Mechanical and Aerospace Engineering
Rutgers, the State University of New Jersey

Buoyancy-Induced Flows
in Nature and in Technology

YOGESH JALURIA

- **Recognized for:**

  research in natural convection heat transfer, thermal processing of materials, and computational heat transfer.

INTRODUCTION BY

Theodore L. Bergman

Professor and Head
Department of Mechanical Engineering
University of Connecticut
Storrs, Connecticut

Areas of Applied Research

- *Thermal Processing of Optical Fibers*
- *Transport in Extrusion of Polymeric Materials including Food Products*
- *Chemical Vapor Deposition*
- *Fires in Enclosures*
- *Cooling of Electronic Equipment*
- *Energy Storage and Solar Energy Systems*
- *Environmental Convection*
- *Design and Optimization of Thermal Systems*

Underlying Physical Processes

- *Buoyancy-Induced Flows*
- *Mixed Convection*
- *Buoyancy Effects in Solid-Liquid Phase Change*
- *Modeling and Experimentation of Buoyancy-Affected Transport Including:*

  -conjugate effects

  -highly variable properties

  -complicated geometries

  -moving boundaries

  -free surface phenomena

  -chemically-reacting and turbulent flows

  -instability

  -stratification

Scholarly Contributions

- *Sole Author of Three Books*
- *Co-Author of Three Additional Books*
- *Over 145 Refereed Journal Articles*
- *15 Chapters in Books*
- *Over 100 Refereed Conference Proceedings Publications*
- *About 100 other Publications*
- *14 Published Invited Keynote Presentations*
- *Multiple Patents and Copyrights*

Honors and Awards

- *ASME-AIChE Max Jakob Memorial Award - 2002*
- *ASME Freeman Scholar Award - 2000*
- *ASME Worcester Reed Warner Medal - 1999*
- *ASME Heat Transfer Memorial Award - 1995*
- *Distinguished Alumni Award - Indian Institute of Technology, Delhi - 1994*
- *Fellow of ASME - 1991*

BUOYANCY-INDUCED FLOWS IN NATURE AND IN TECHNOLOGY

YOGESH JALURIA

Department of Mechanical and Aerospace Engineering

Rutgers, the State University of New Jersey

New Brunswick, NJ 08903

ROBERT HENRY THURSTON LECTURE

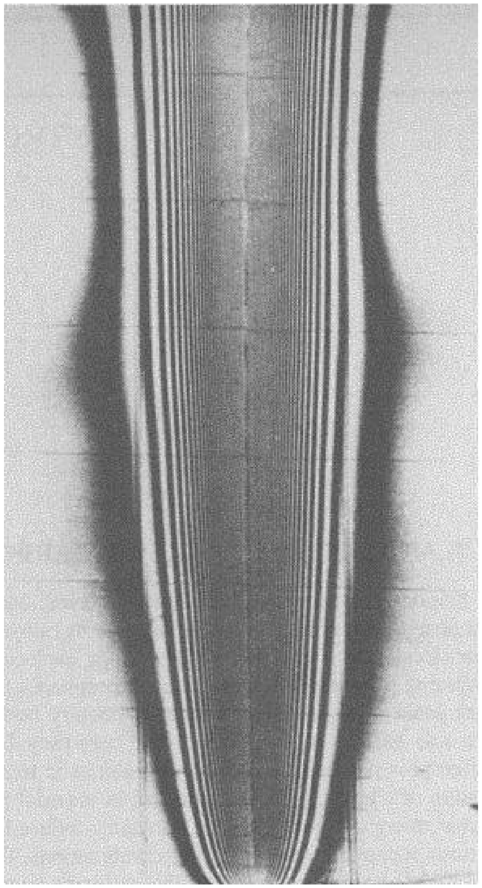
2003 ASME IMECE, WASHINGTON, DC

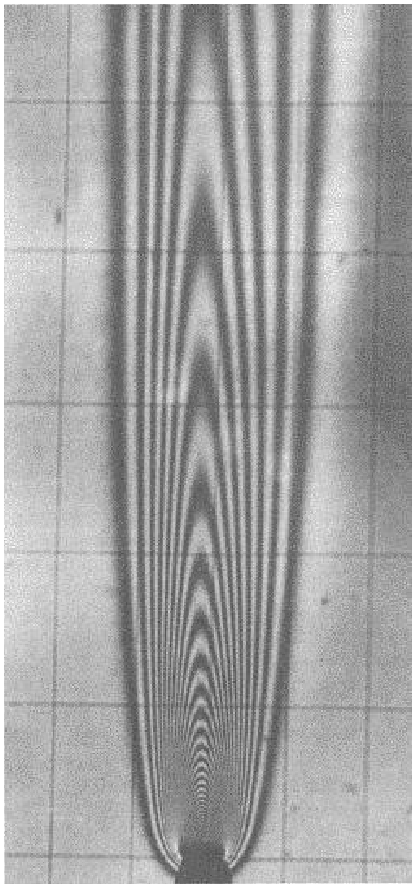
Outline

- Introduction
- Basic Mechanisms
- Flows in Nature
- Environmental and Energy Processes
- Fires
- Safety and Security
- Cooling of Electronic Systems
- Materials Processing
- Microgravity Transport
- Conclusions and Future Research Needs

Introduction

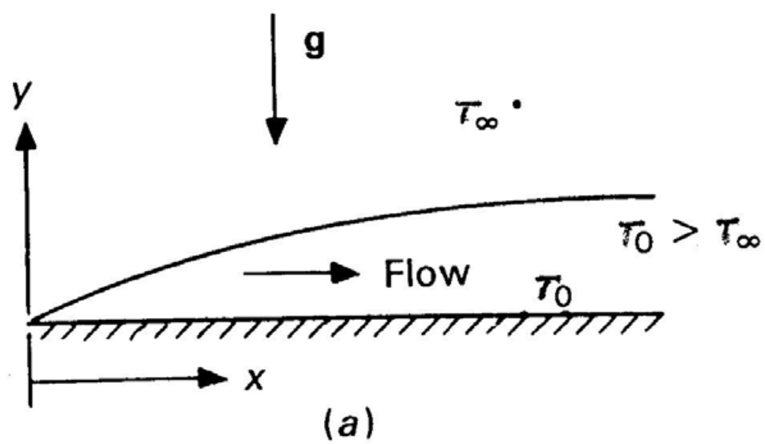
Interferograms of Vertical Flow Over a Heated Surface and Over a Horizontal Heated Wire

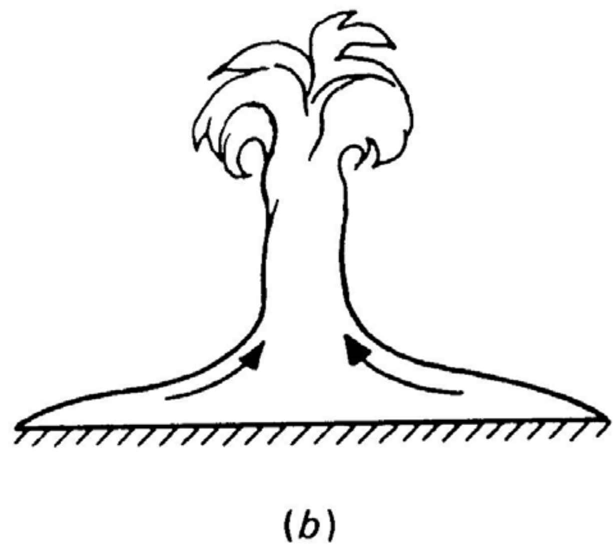




From Polymeropoulos and Gebhart (1967) and Gebhart et al. (1970)

Idealized Natural Convection Flow over Hot Horizontal Surfaces Facing Upward

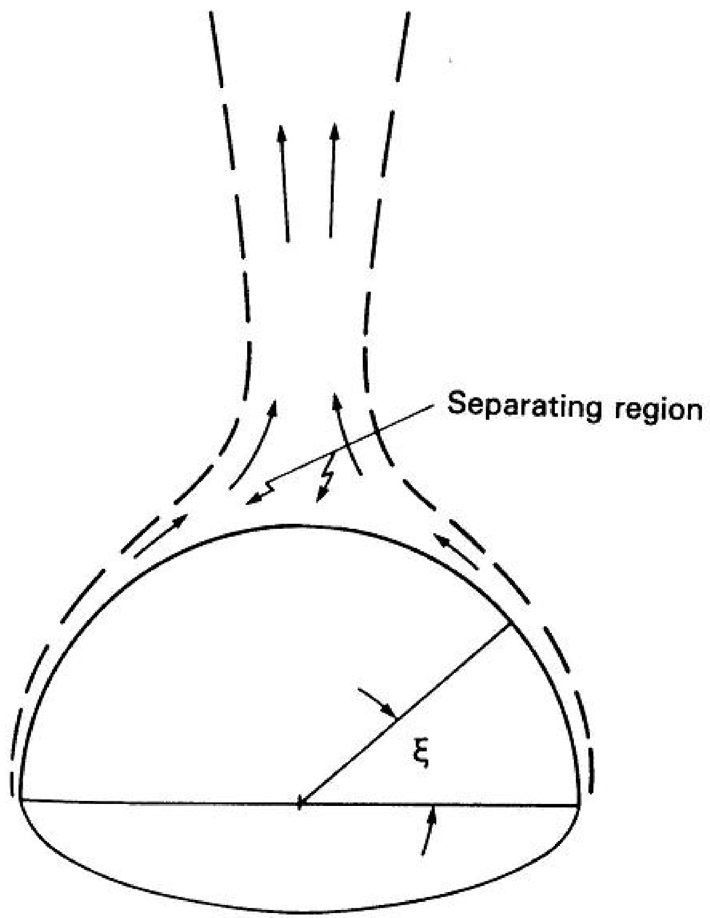




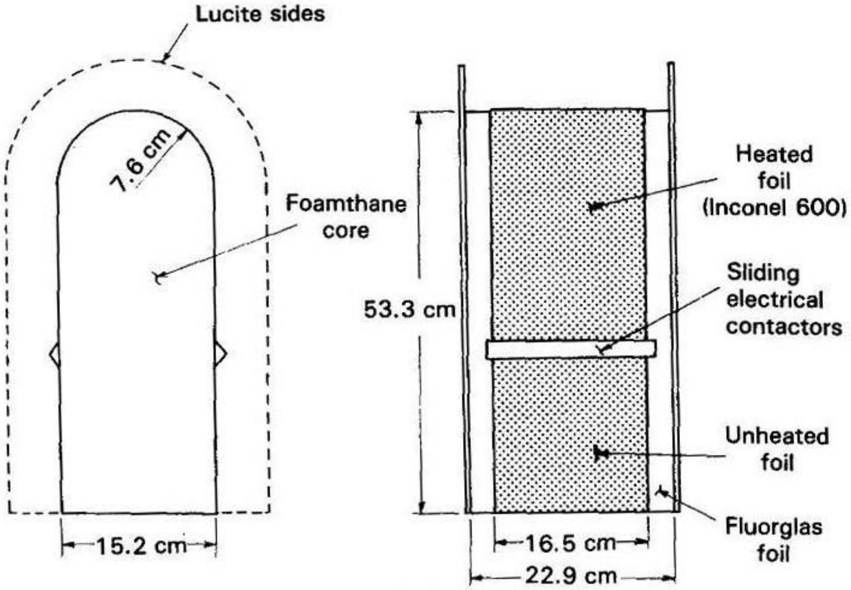
(a) Semi-infinite surface

(b) Finite surface

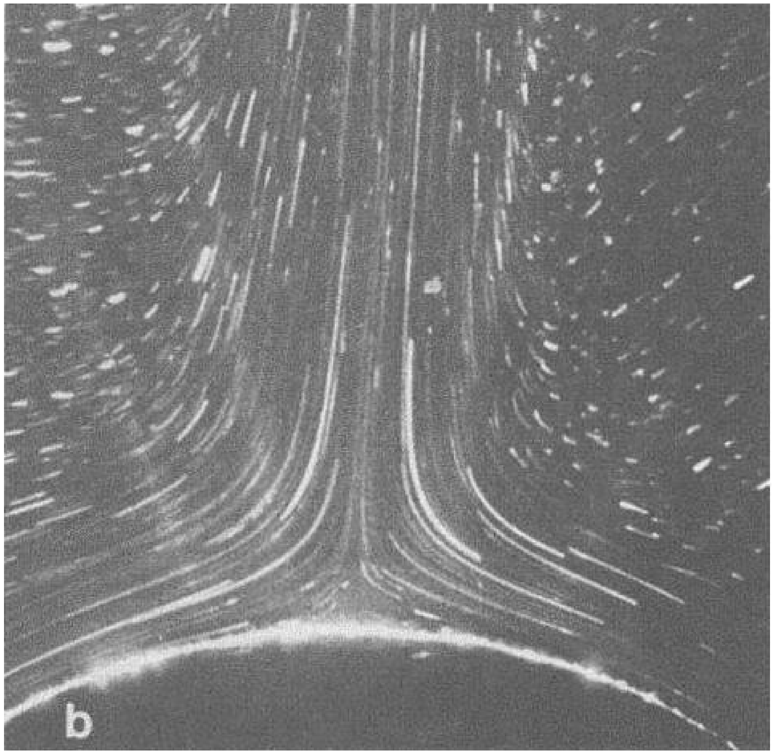
Flow Separation above a Heated Body



Steady Natural Convection in the Wake of a Horizontal Heated Cylindrical Surface



(a)

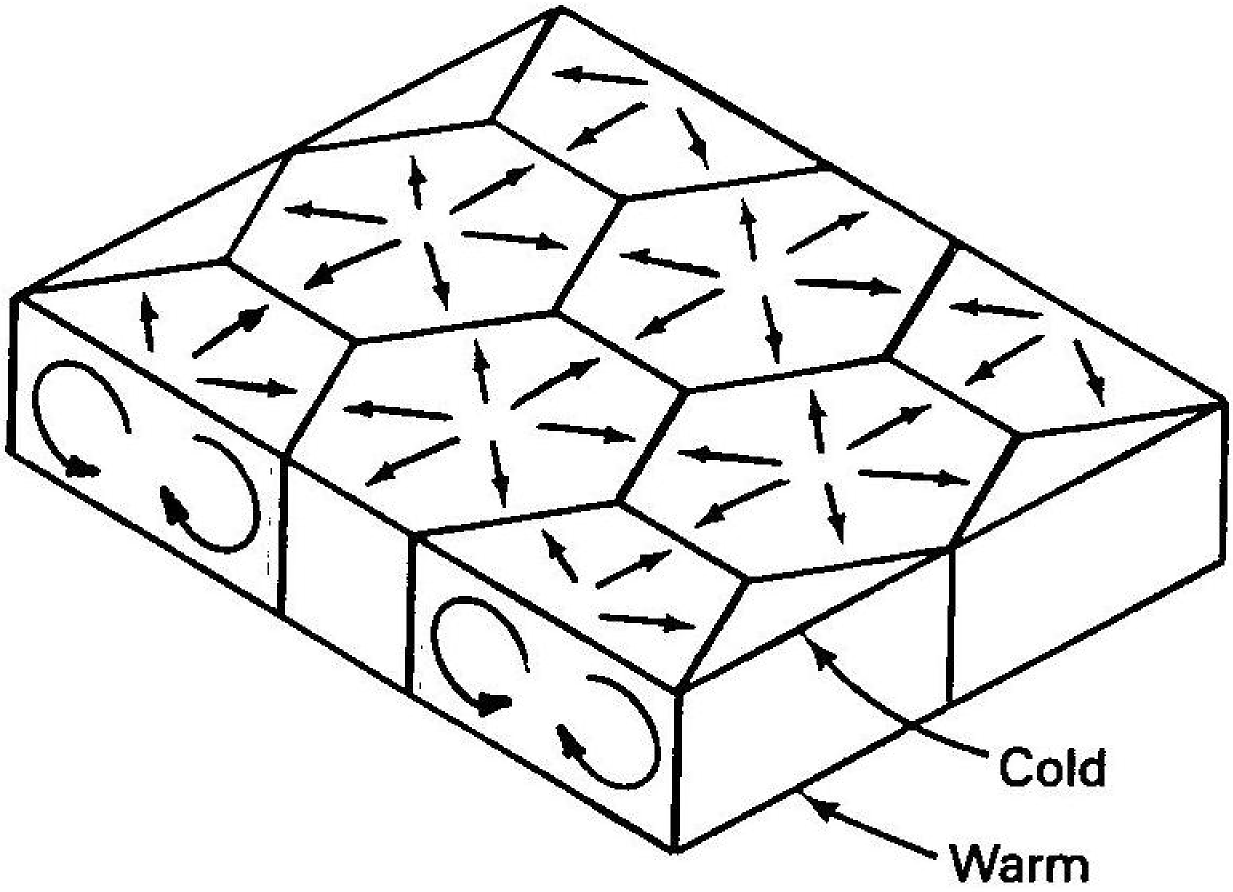


(a) Flow-generating geometry;

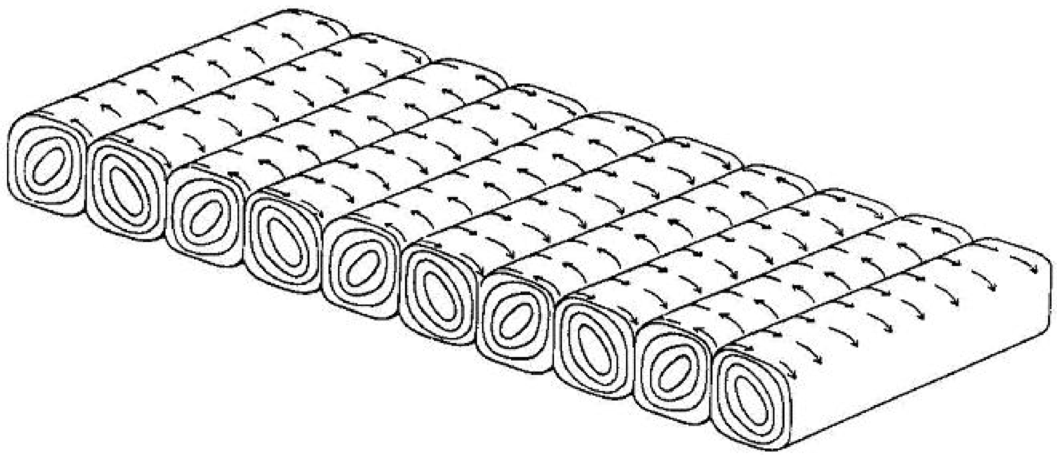
(b) Pattern of flow at and above the top

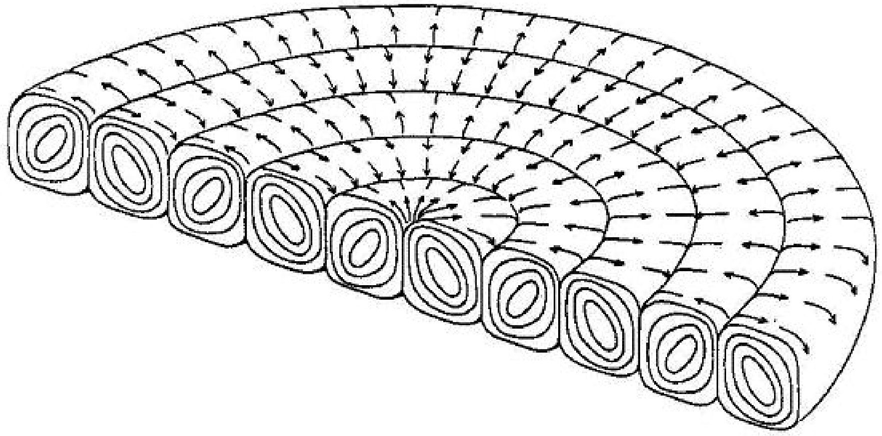
From Pera and Gebhart (1972)

Bénard Cells for Natural Convection in a Horizontal Fluid Layer

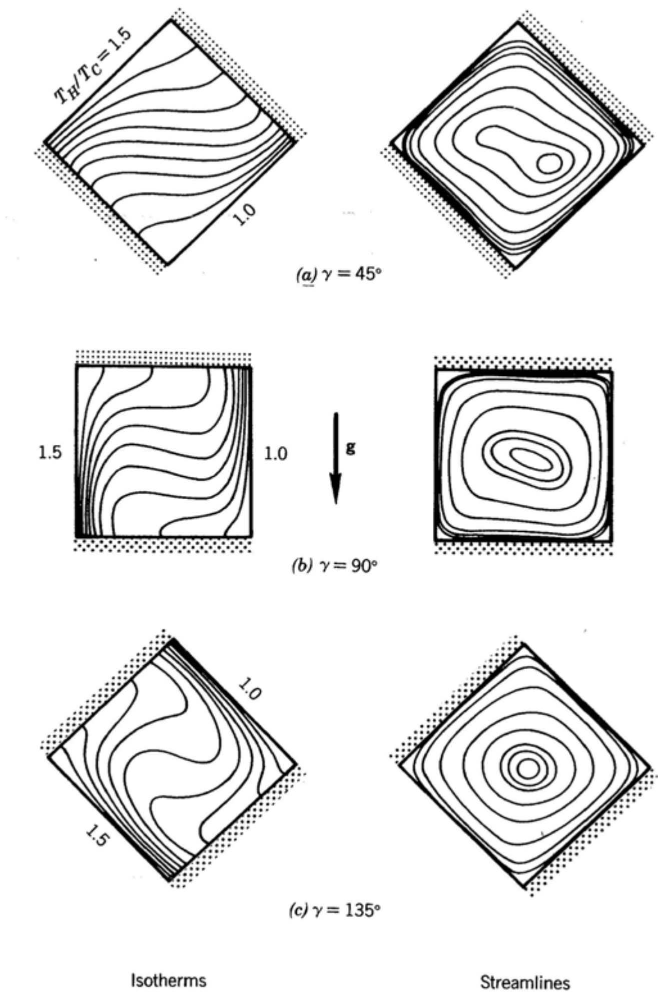


Roll-Shaped Cells in a Rectangular or Circular Container



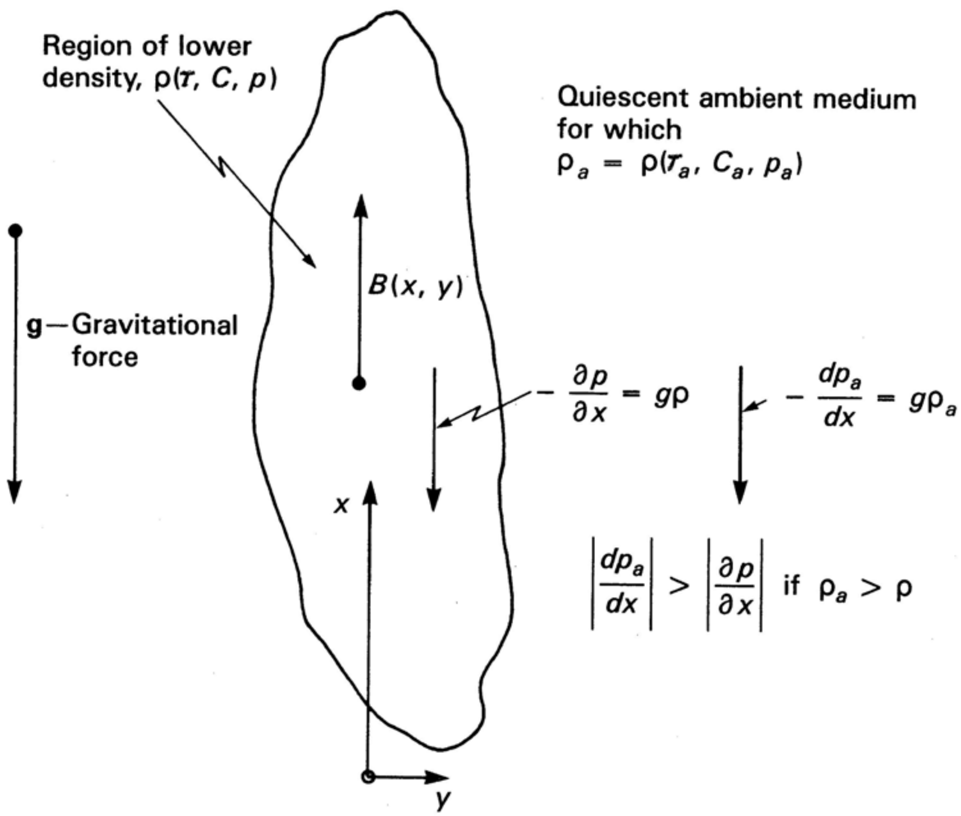


Buoyancy-Induced Flow in Rectangular Enclosures



Basic Mechanisms

Buoyancy Force



Buoyancy Term

$p = p_a + p_m$

Pressure   Hydrostatic Pressure   Motion Pressure

$$\rho \bar{g} - \nabla p = (\rho - \rho_a)\bar{g} - \nabla p_m$$

= Buoyancy – Pressure Gradient

Convection Velocity

$$\frac{1}{2}\rho u^2 \approx g\Delta\rho L, \quad \text{g} = \text{gravitational acceleration, L} = \text{Length scale}$$

$$u = O(\sqrt{g\Delta\rho L/\rho}$$

Boussinesq Approximation

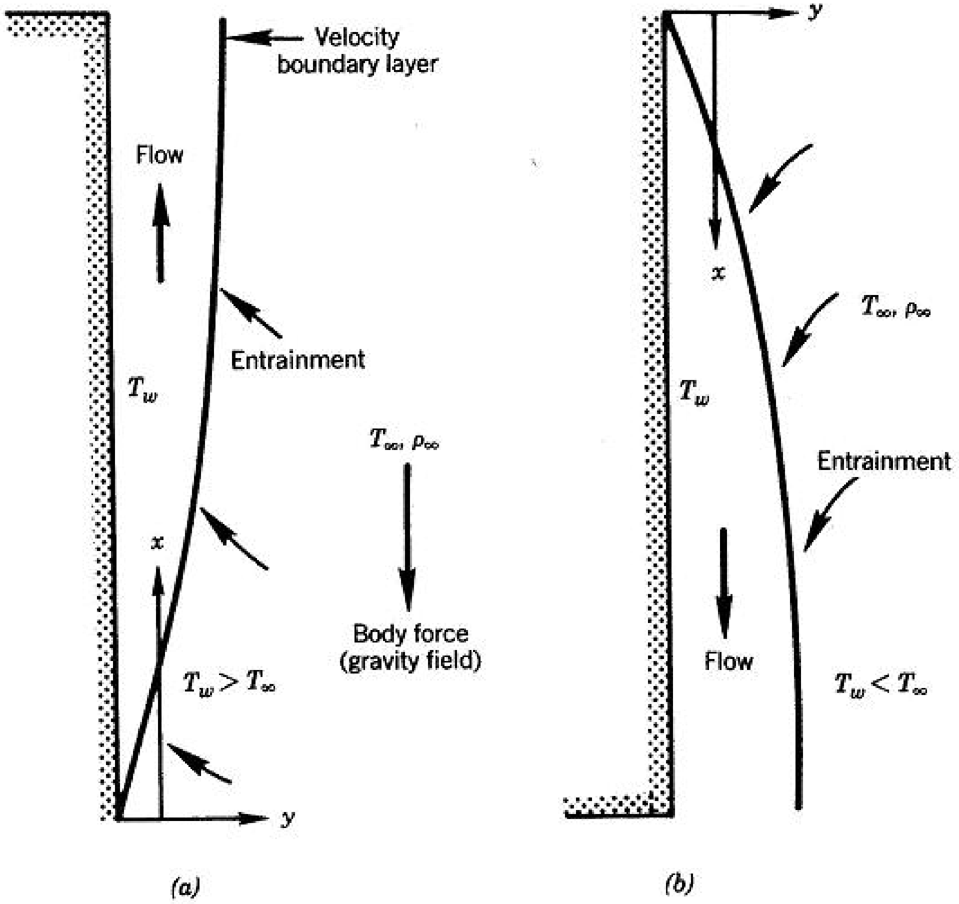
$$\rho_a - \rho = \rho\beta(T - T_a), \quad \beta = \text{coefficient of volumetric expansion}$$

$$Gr = \frac{g\beta(T - T_a)L^3}{\nu^2} = \text{Grashof Number} \approx \frac{\text{Buoyancy force}}{\text{Viscous Force}}$$

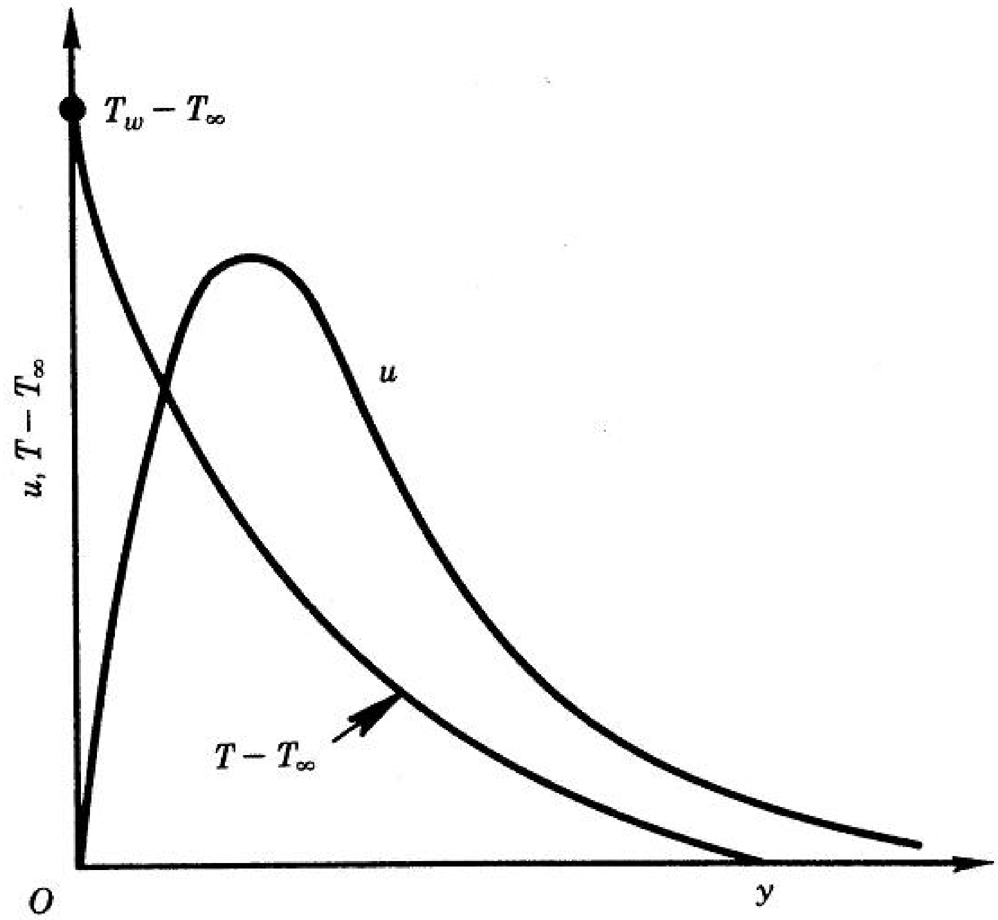
ν = kinematic viscosity

Reynolds Number, Re $\approx \sqrt{\text{Gr}}$

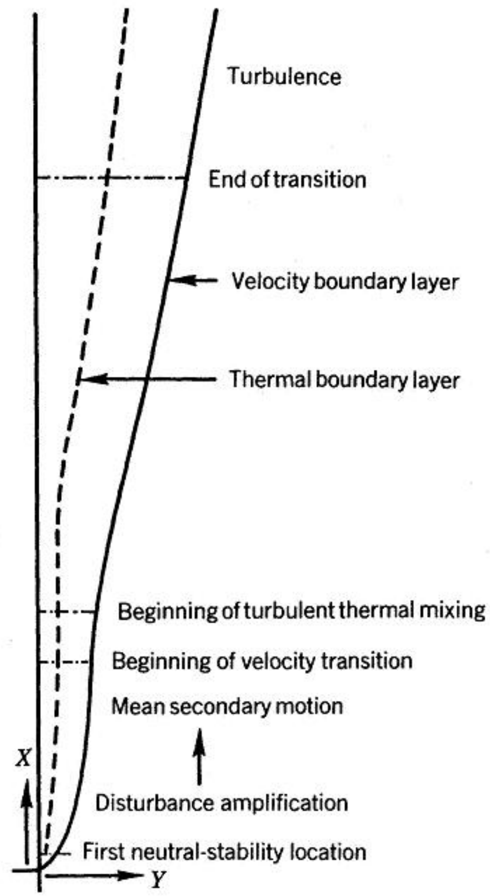
Buoyancy-Driven Flow Over a Flat Vertical Surface



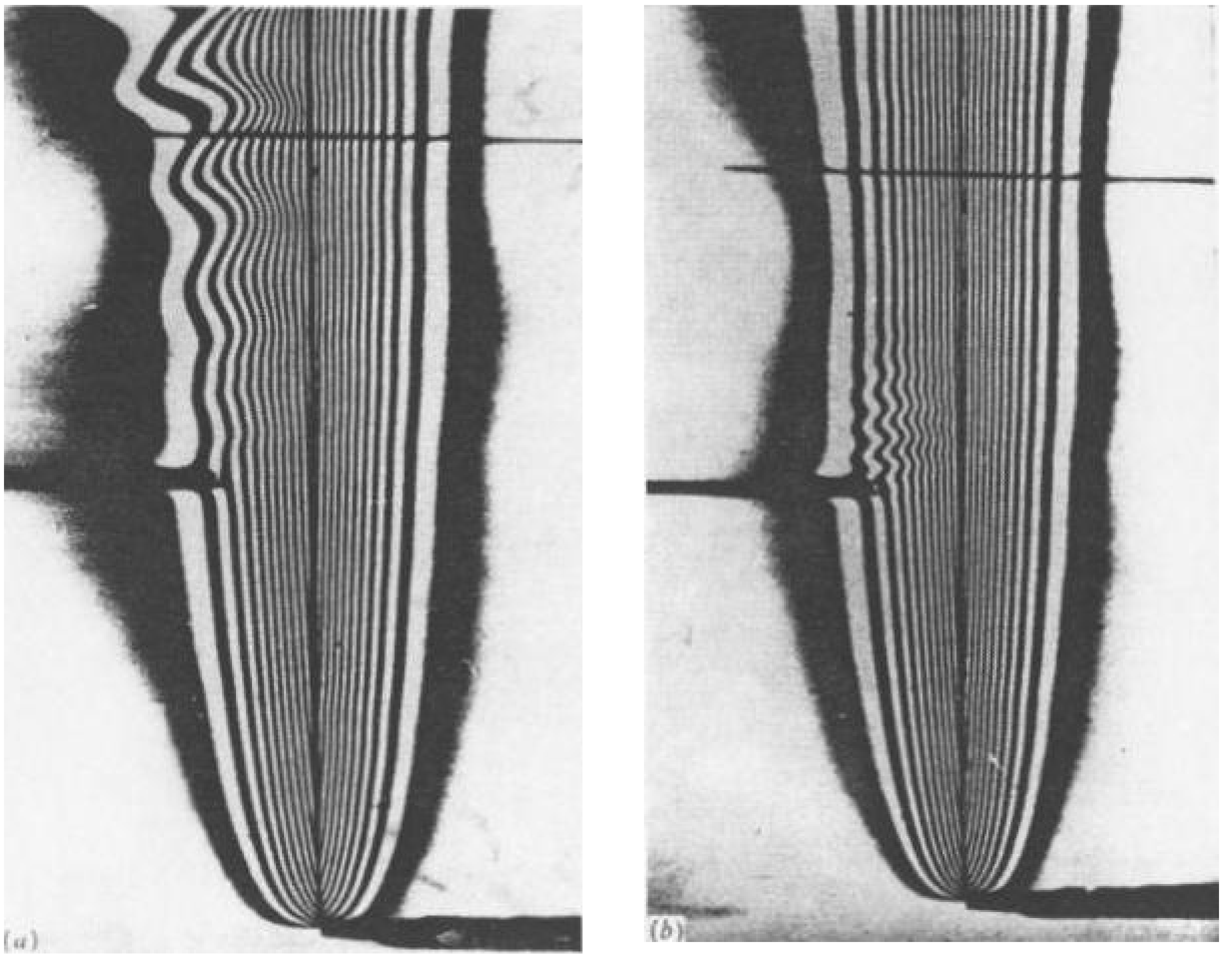
Velocity and Temperature Profiles



Sequence of Events in a Vertical Buoyancy-Driven Flow



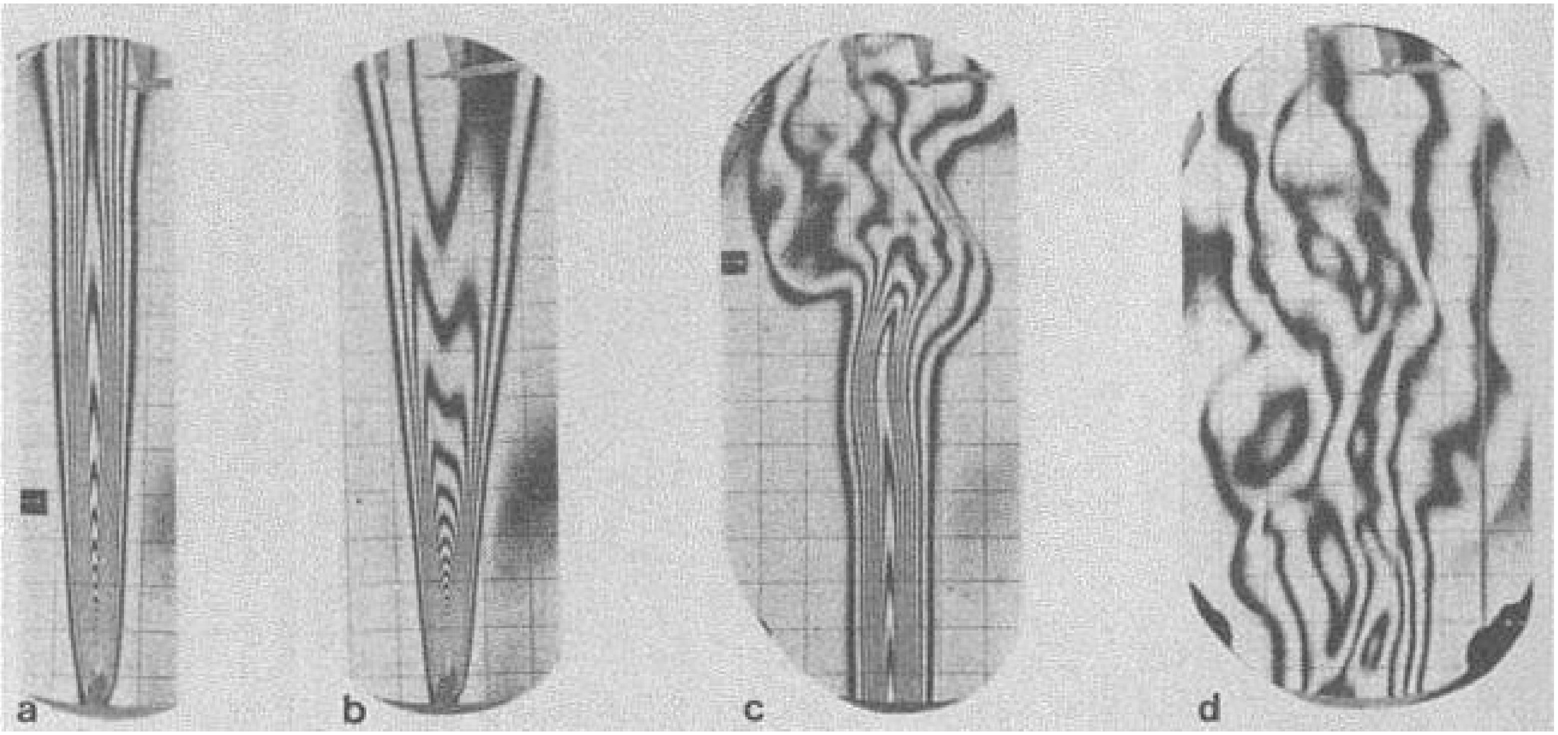
Interferograms of Oscillations in the Boundary Layer Flow Over a Heated Vertical Plate



(a) The disturbance is amplified
(b) The disturbance is damped.

From Polymeropoulos and Gebhart (1967)

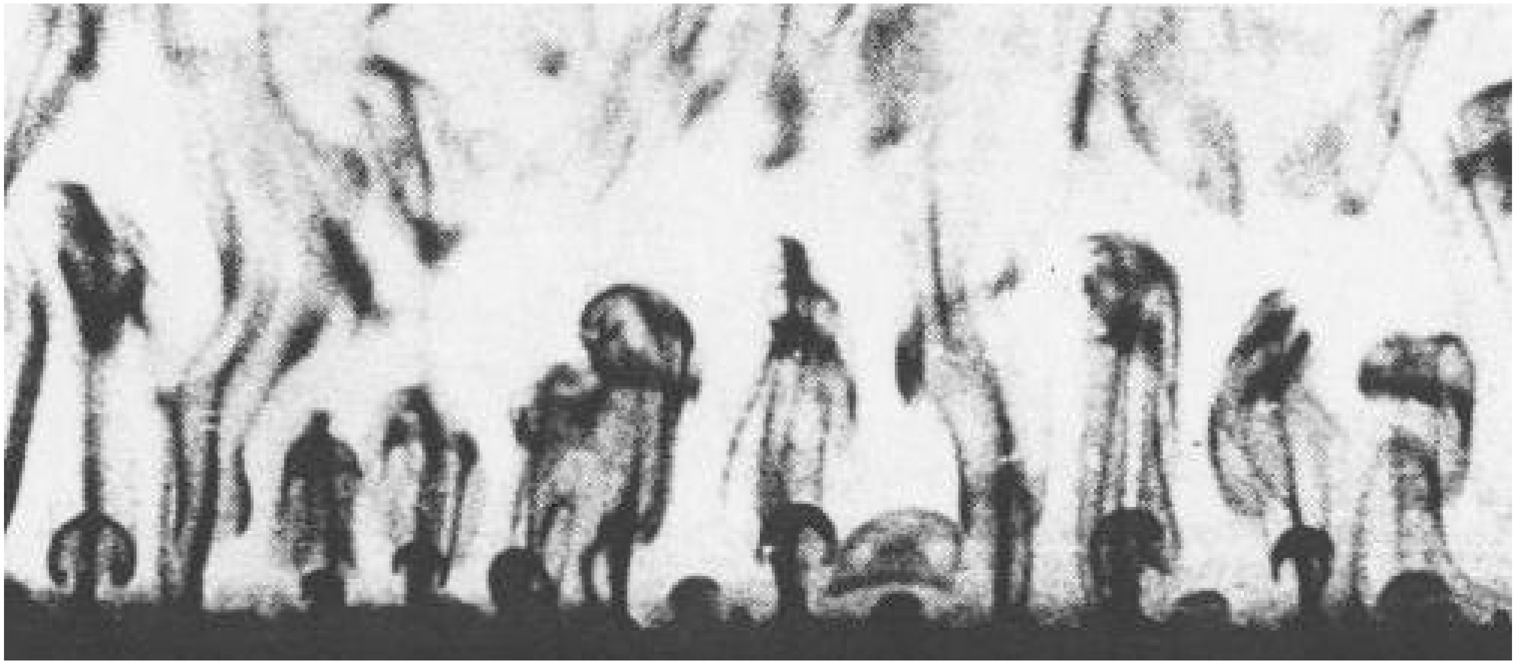
Interferograms of Flow Instability in Two-Dimensional Plumes



(a) G = 68.8, x = 5.1 cm, Q = 50 W/m;
(b) G = 68.8, x = 5.1 cm, Q = 50 W/m
(c) G = 186.0, x = 20.3 cm, Q = 98.1 W/m;
(d) G = 228.0, x = 30.5 cm, Q = 98.1 W/m

From Pera and Gebhart (1975)

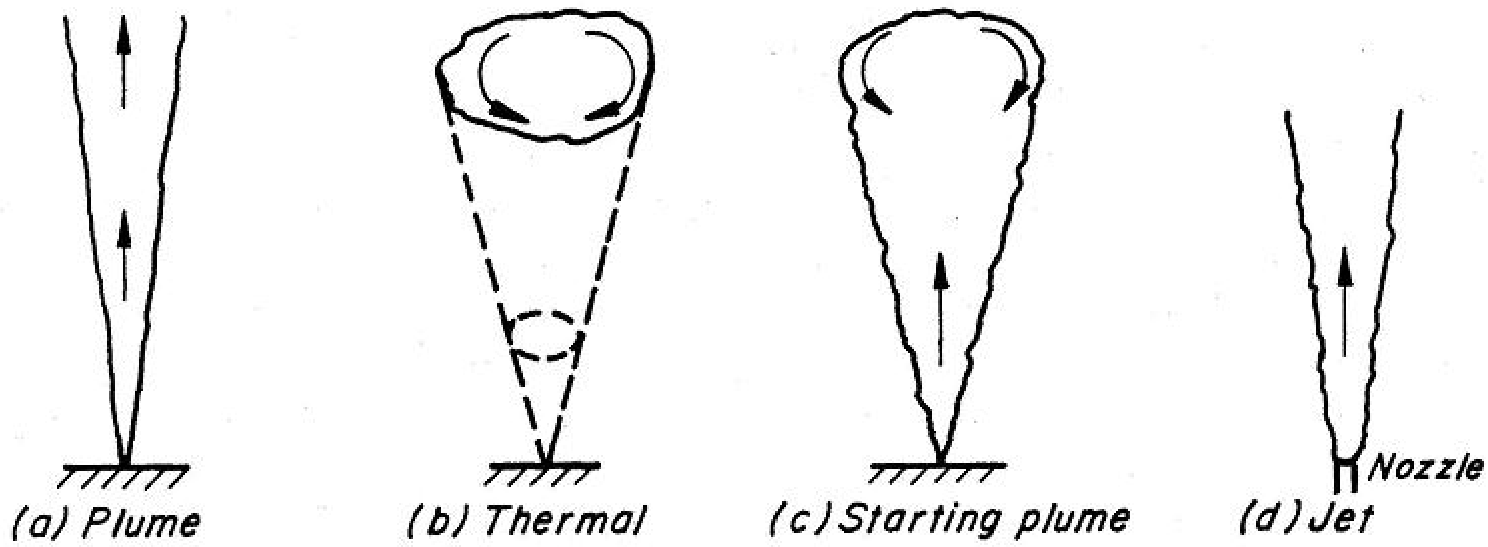
‘Thermals’ Rising from a Heated Horizontal Boundary under a Layer of Water



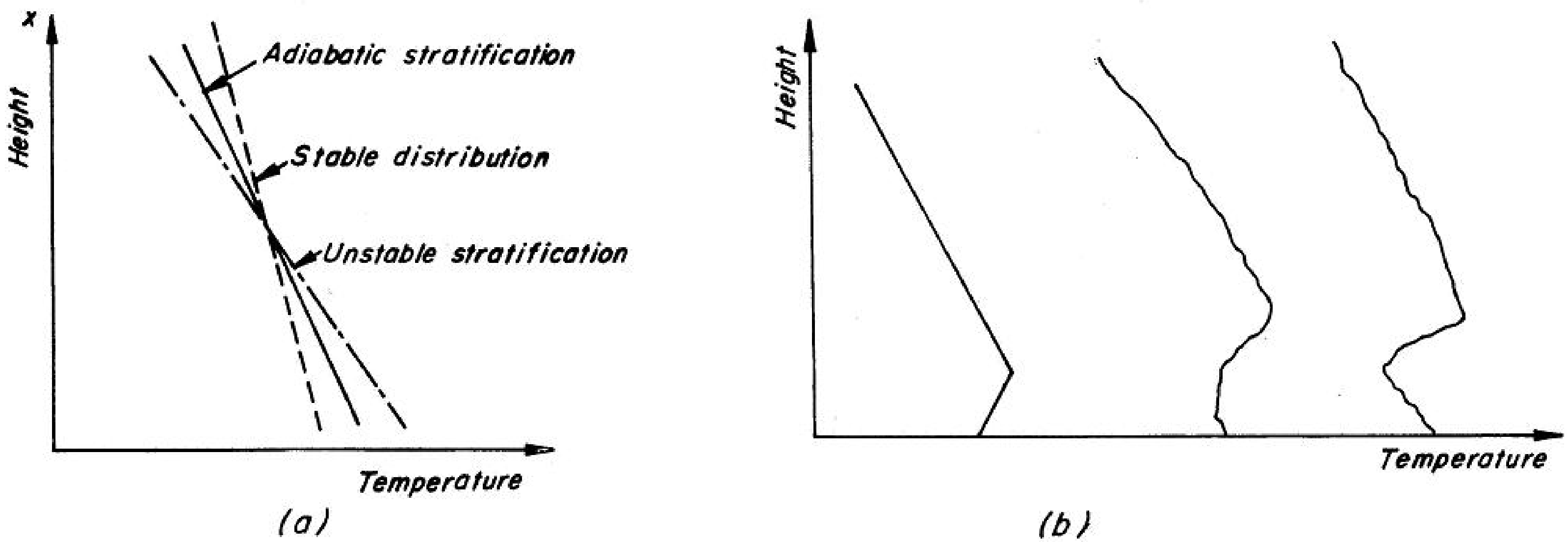
From Sparrow, Husar and Goldstein (1970)

Flows in Nature

Typical Freely Rising Flows



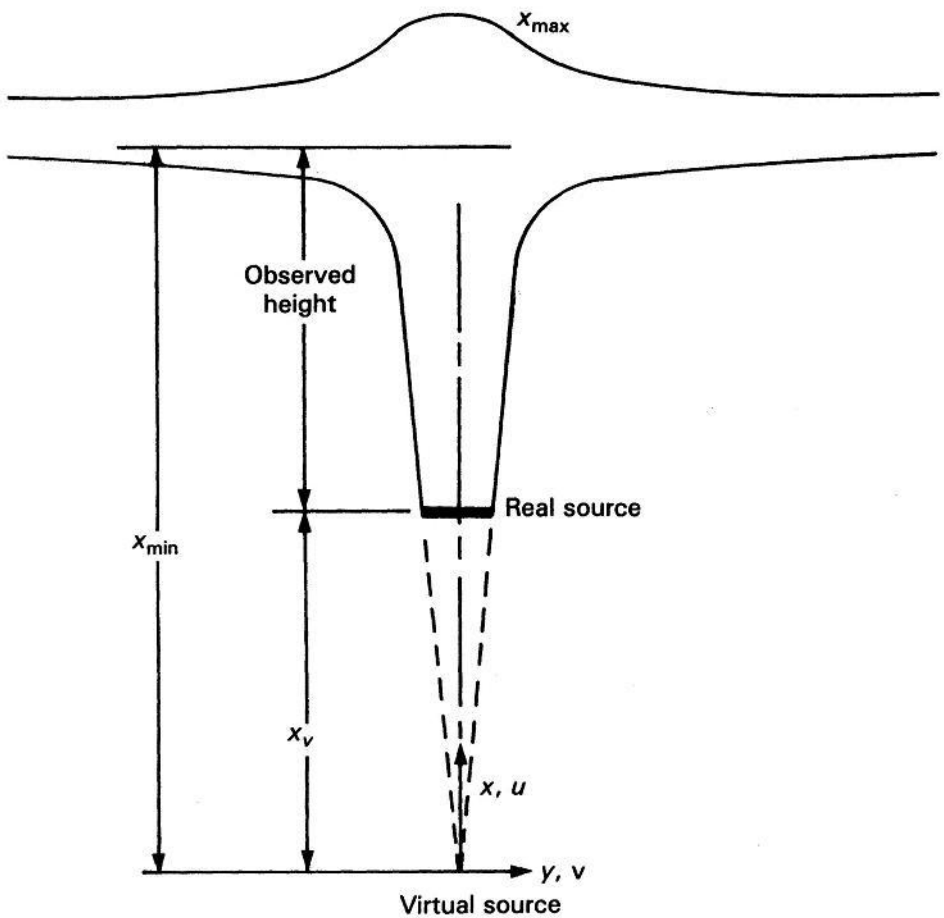
Thermal Stratification



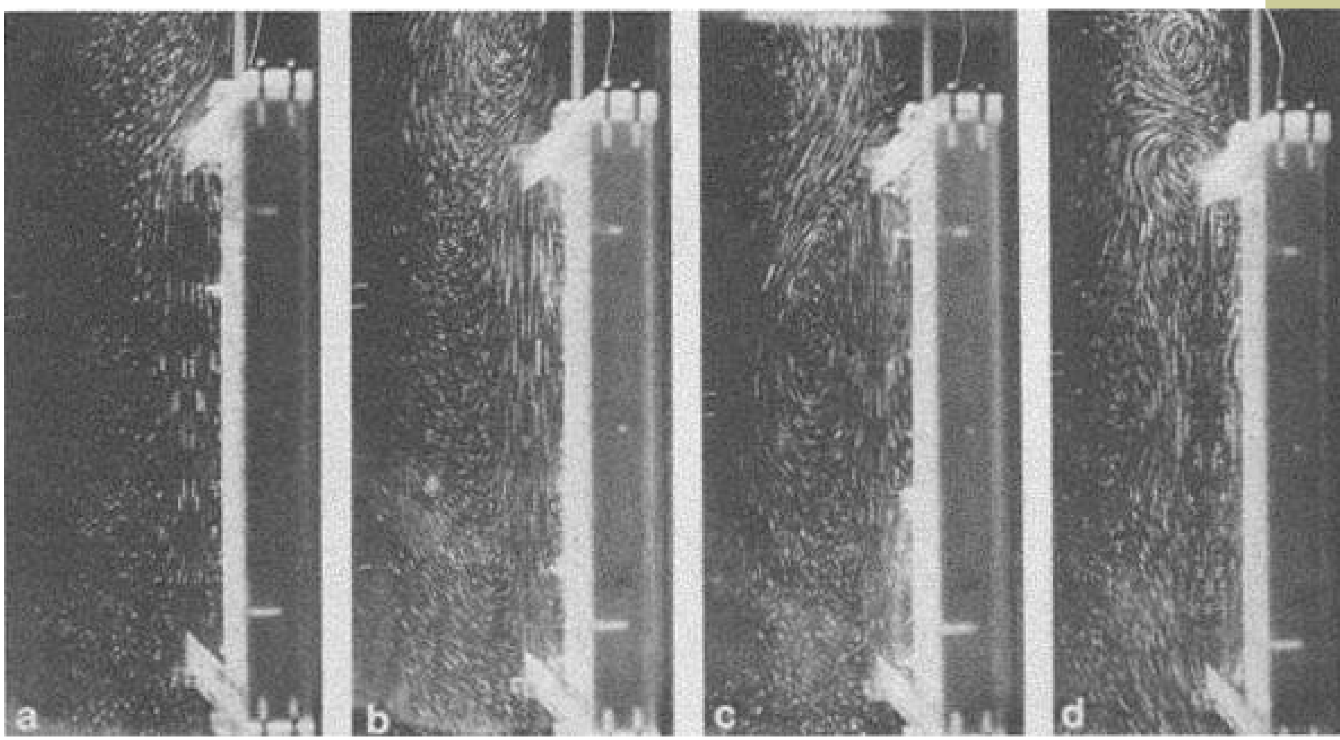
(a) Temperature distributions for stable, unstable and adiabatic thermal stratification

(b) Typical temperature distribution for atmospheric inversion

Plume Rising in a Stably Stratified Region



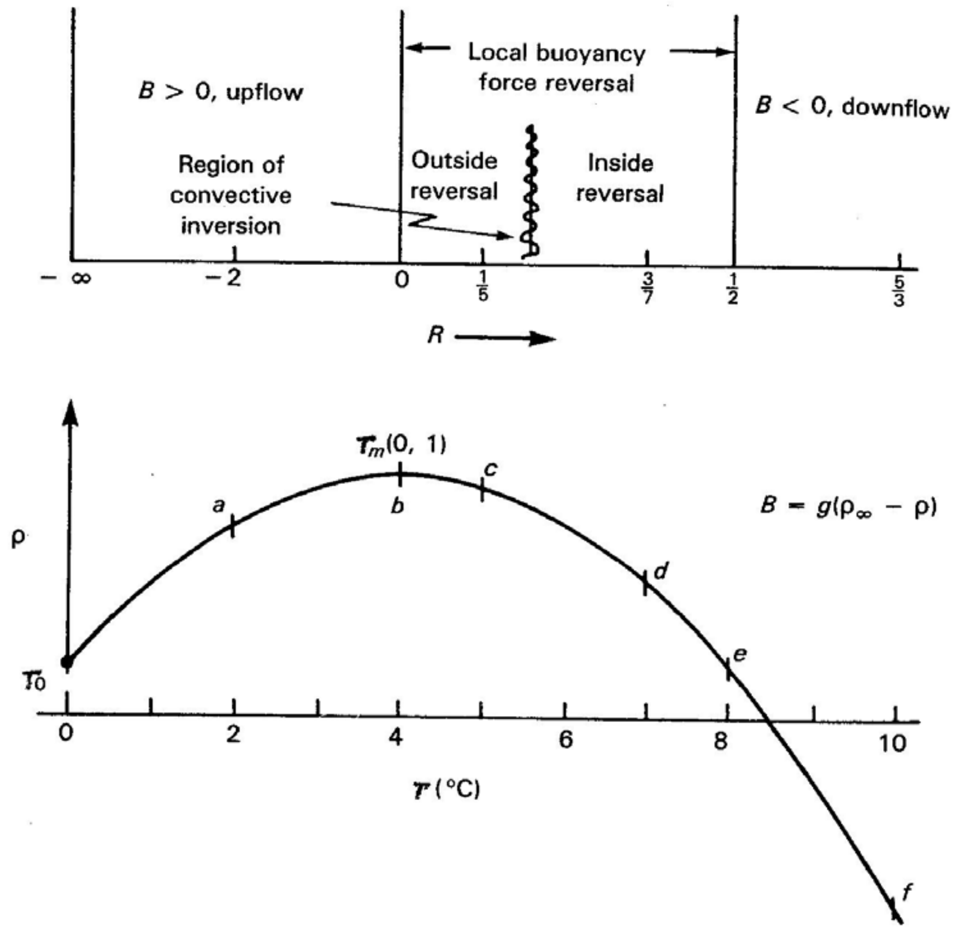
Flow Adjacent to a Vertical Ice Slab Melting in Pure Water



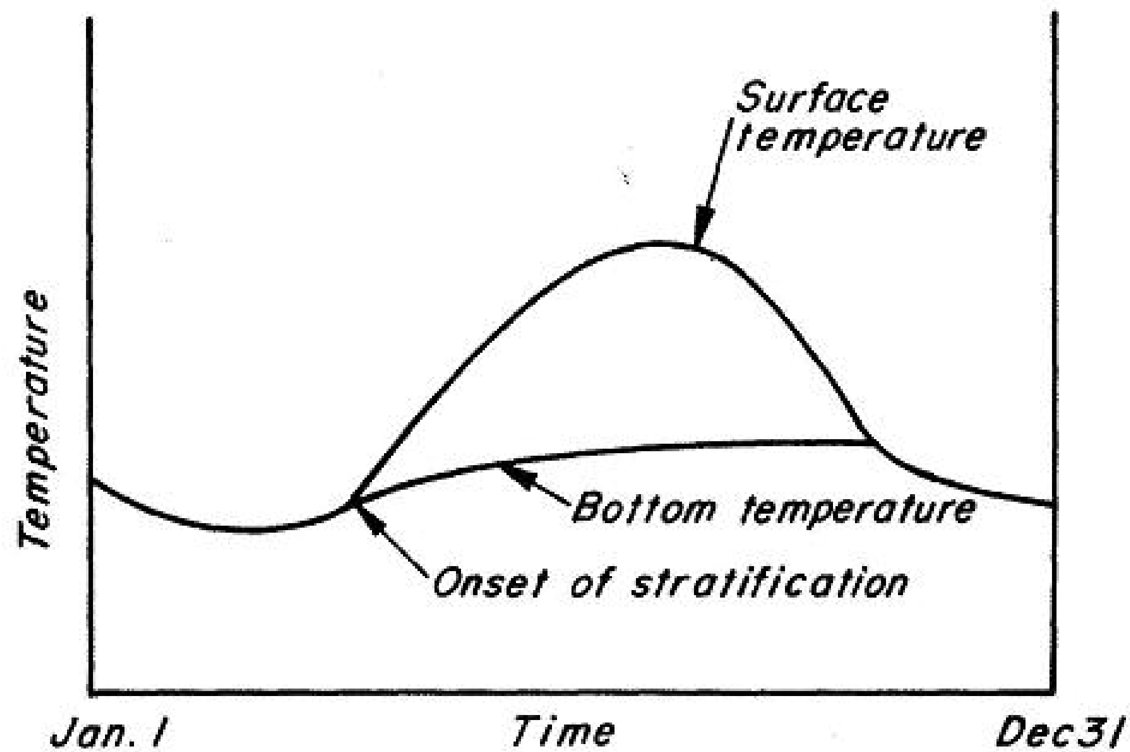
From Carey and Gebhart (1981)

The corresponding ambient temperatures, R values (which give the magnitude and direction of buoyancy), and exposure times are
(a) 3.90 °C, R = - 0.033, 6 s; (b) 4.05 °C, R = 0.005, 10 s;
(c) 4.40 °C, R = 0.084, 10 s; (d) 4.70 °C, R = 0.143, 10 s.

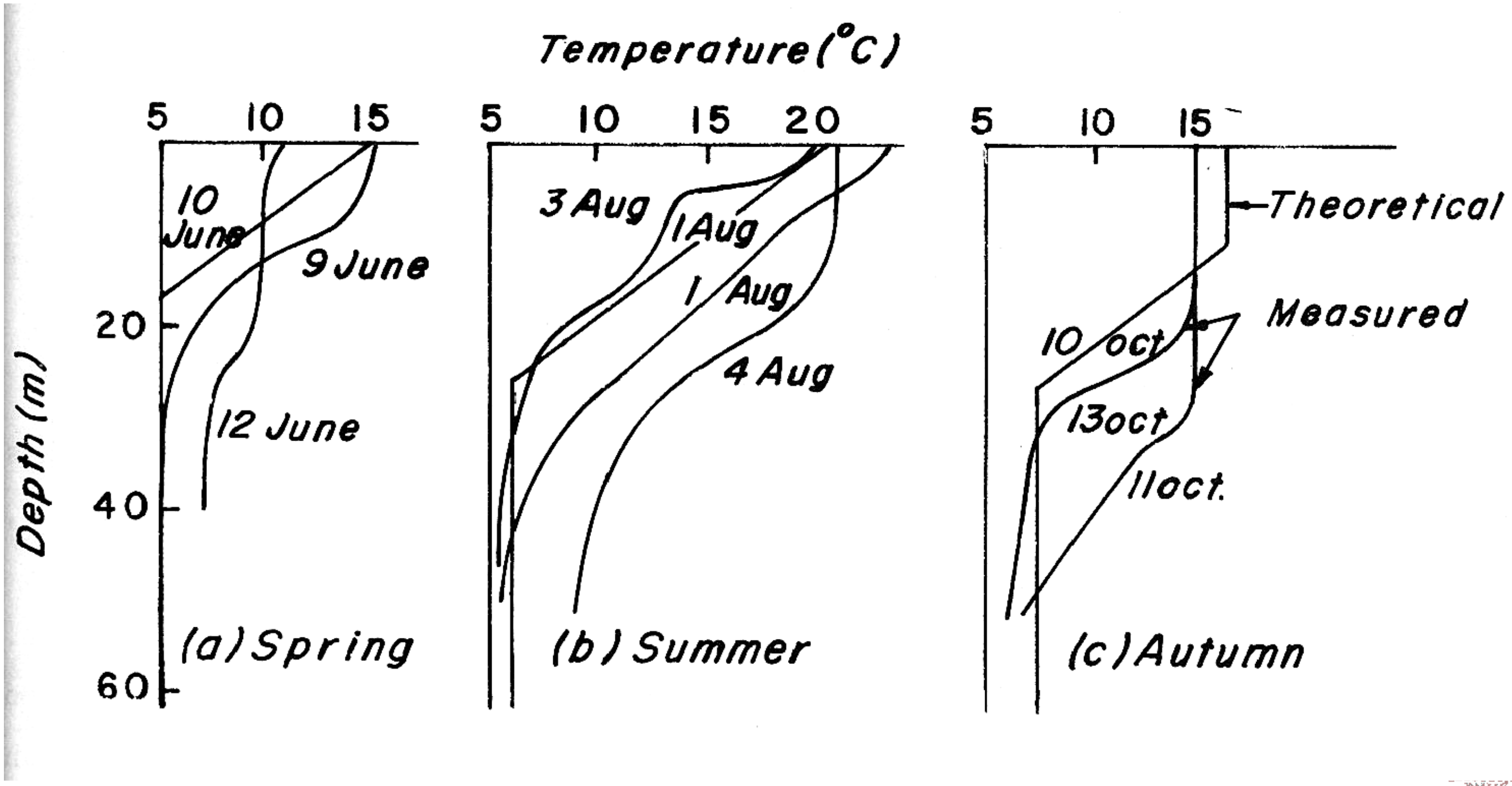
Variation of Water Density with Temperature



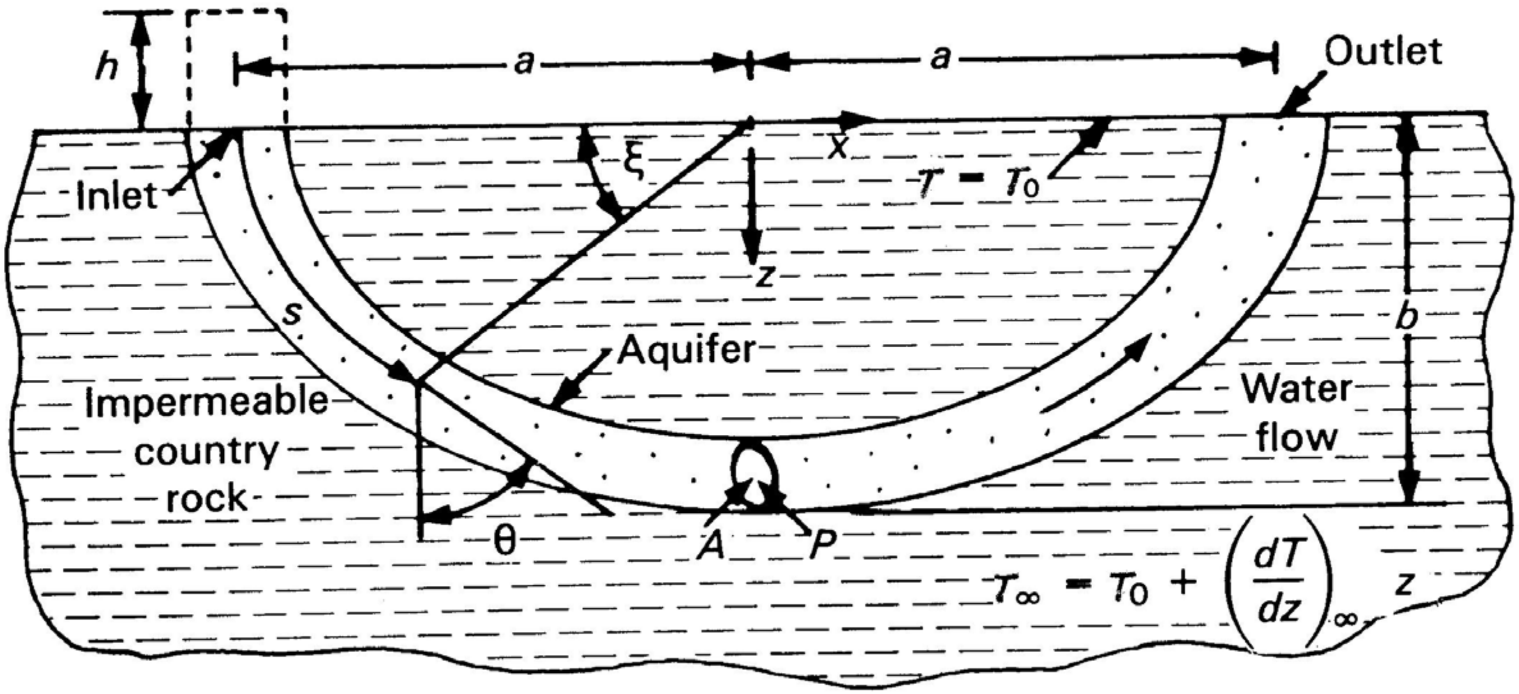
Qualitative Sketch of the Stratification Cycle of a Water Body



Temperature Distributions in a Stratified Water Body



Schematic of an Open-Loop Thermosyphon (the Aquifer)



From Torrance (1979)

Environmental and Energy Processes

Buoyancy-Induced Flow in Environmental and Energy Systems

- Removal of Heat and Pollutants: Cooling Towers, Thermal Discharges, Chimneys, Cities
- Furnaces, Boilers, Condensers
- Cooling Systems
- Energy Storage
- Energy Extraction
- Salt-gradient Solar Ponds
- Geothermal Energy
- Ocean Thermal Energy

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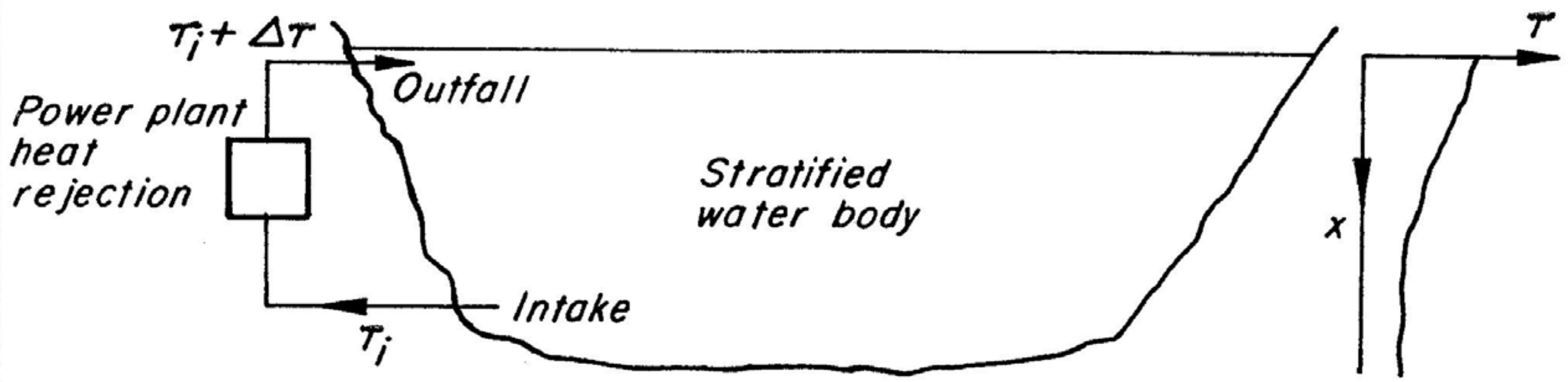
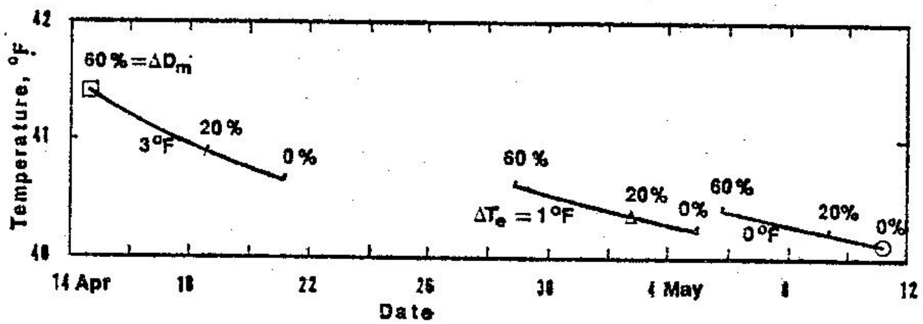
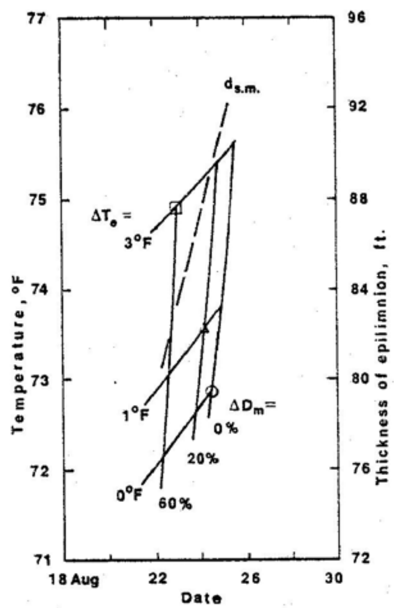
A Sketch of the System for Heat Rejection from a Power Plant to a Lake

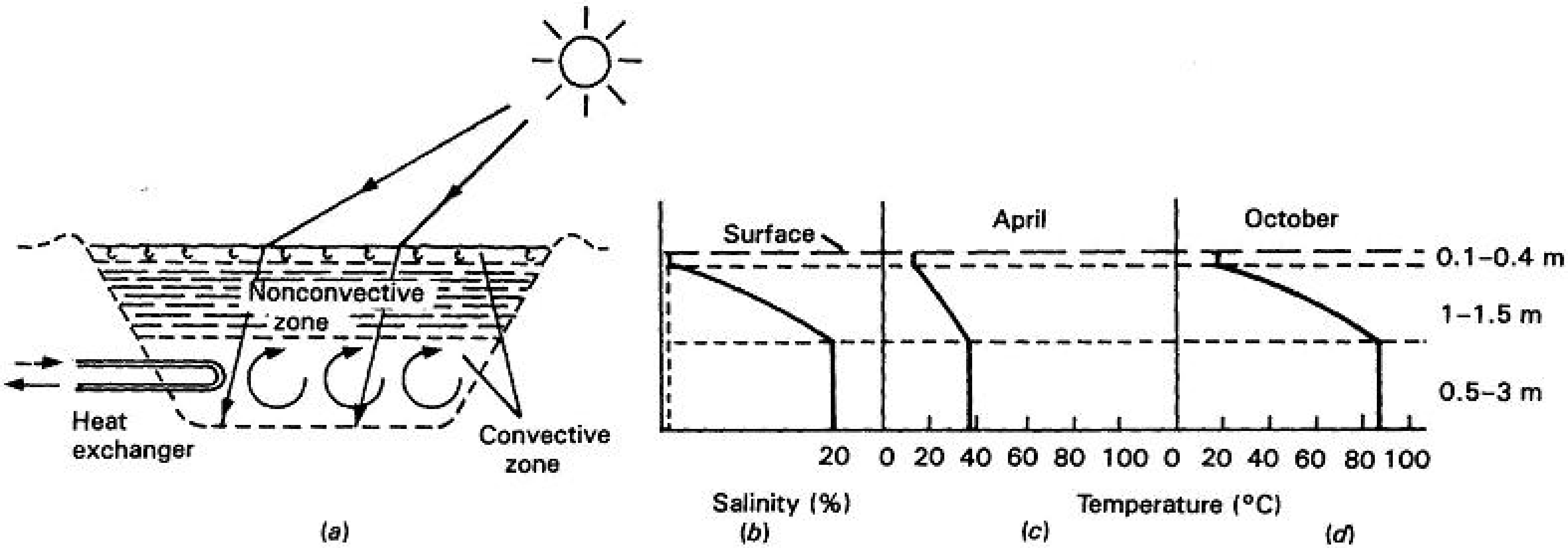


Effects of Heat Rejection from a Power Plant to a Lake





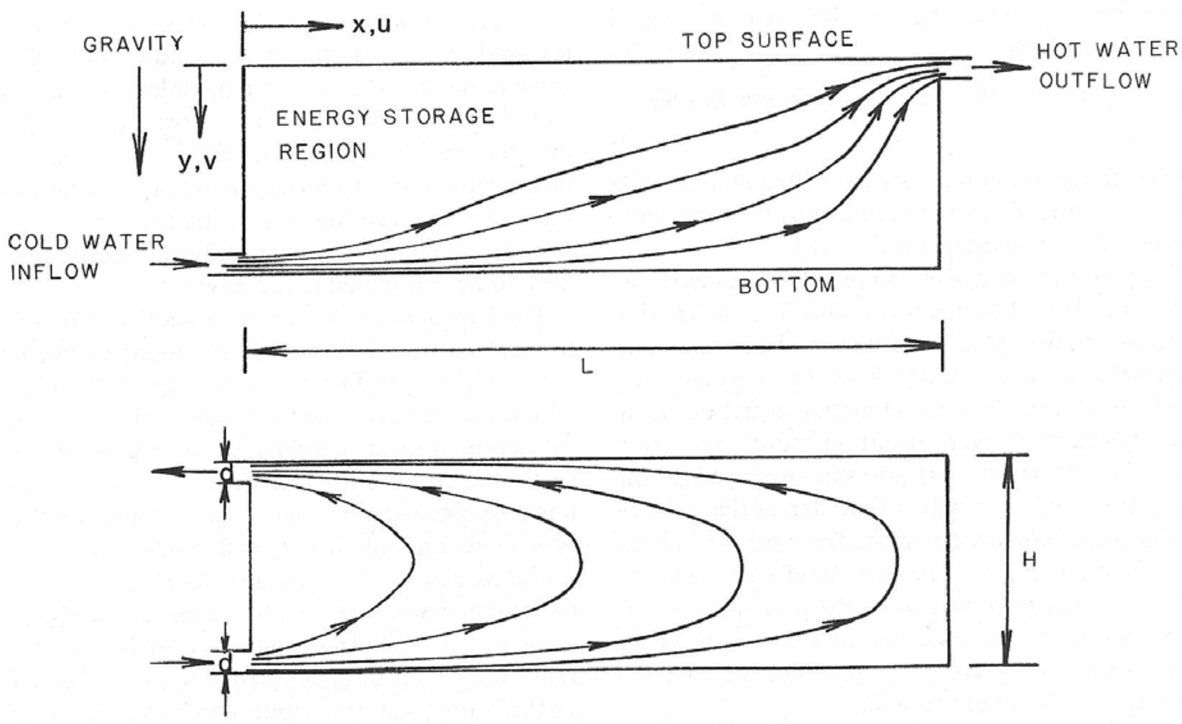
Salt-Gradient Solar Pond



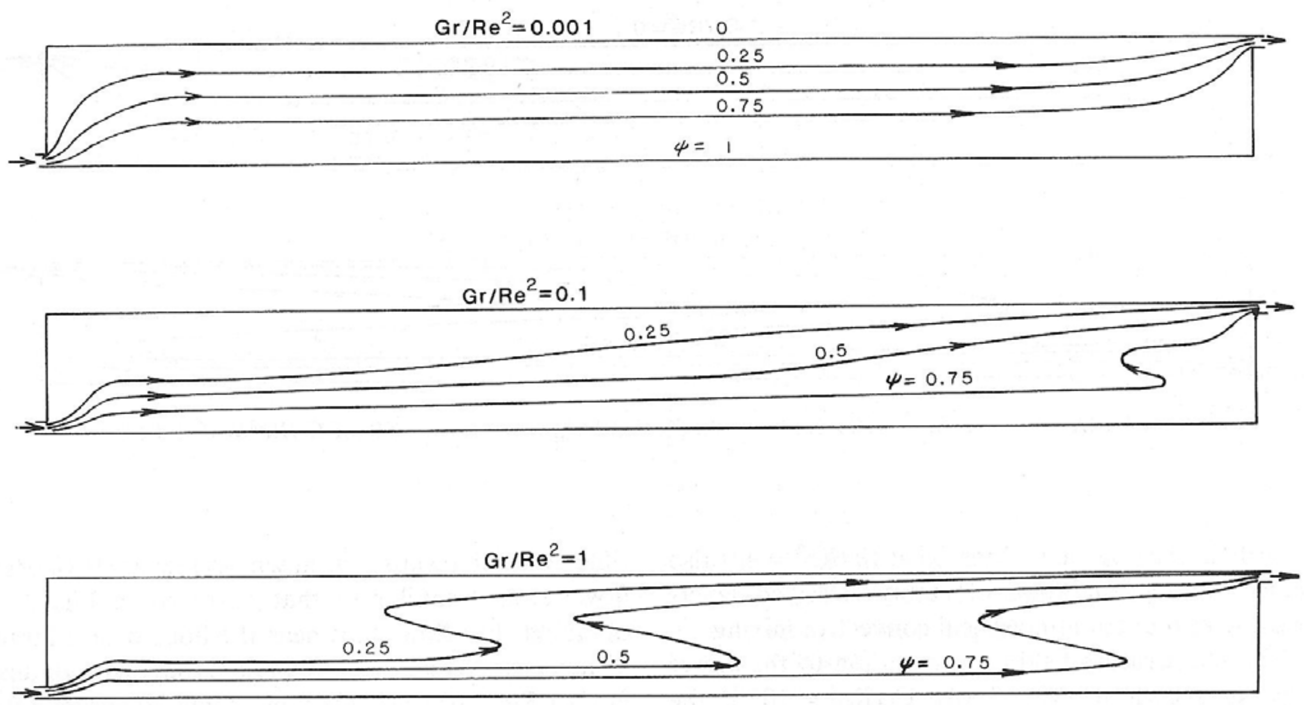
(a) Cross section of a salt gradient solar pond;
(b) salinity profile, a possible stationary configuration
(c and d) temperature profiles, idealized, anticipated in space heating applications. (From Nielsen, 1979)

Rutgers Engineering

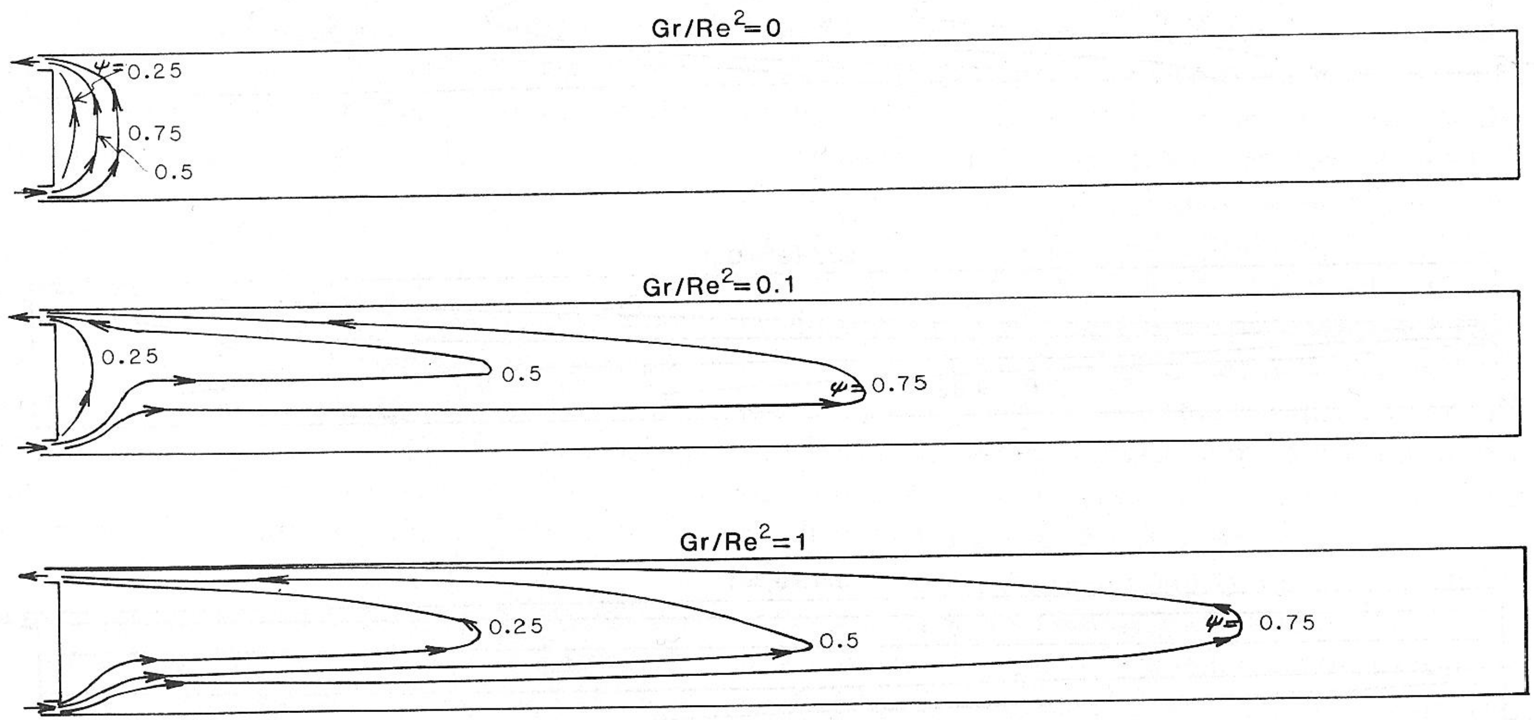
Flow Configurations for Energy Extraction From a Heated Fluid Region



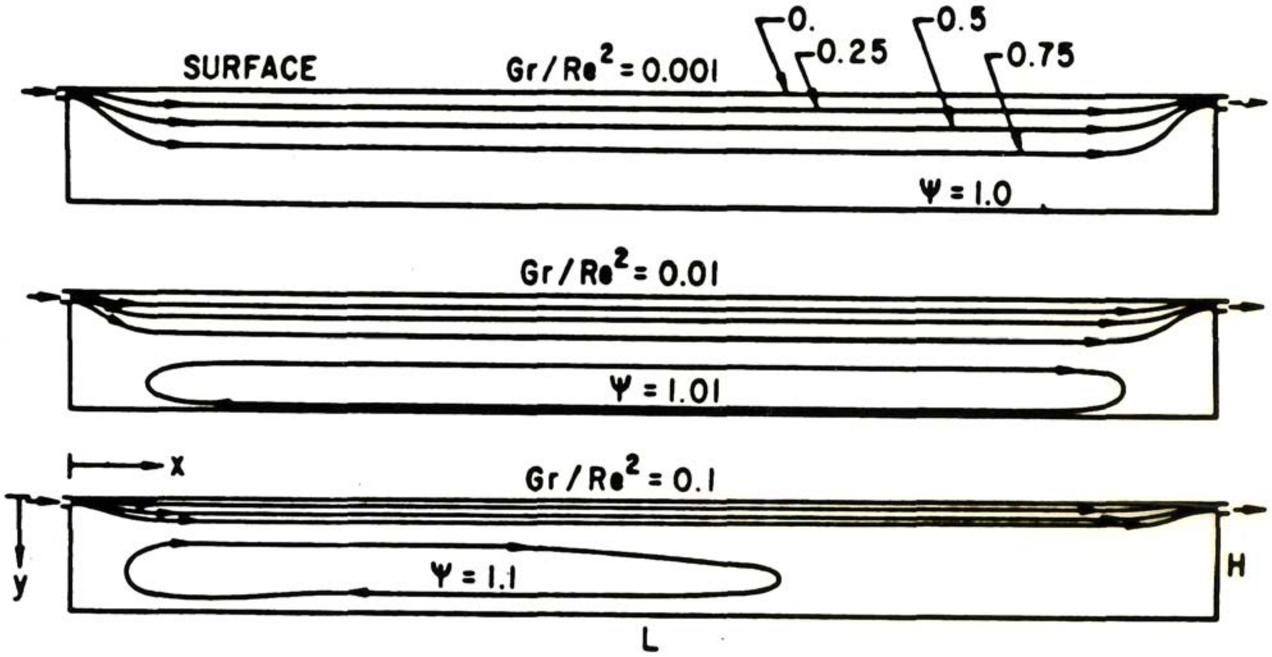
Calculated Streamlines at Re=100



Streamlines for the Same-End Configuration at Re = 1000 for Energy Extraction



Steady-State Streamlines at Re = 100 for Heat Rejection to a Water Body

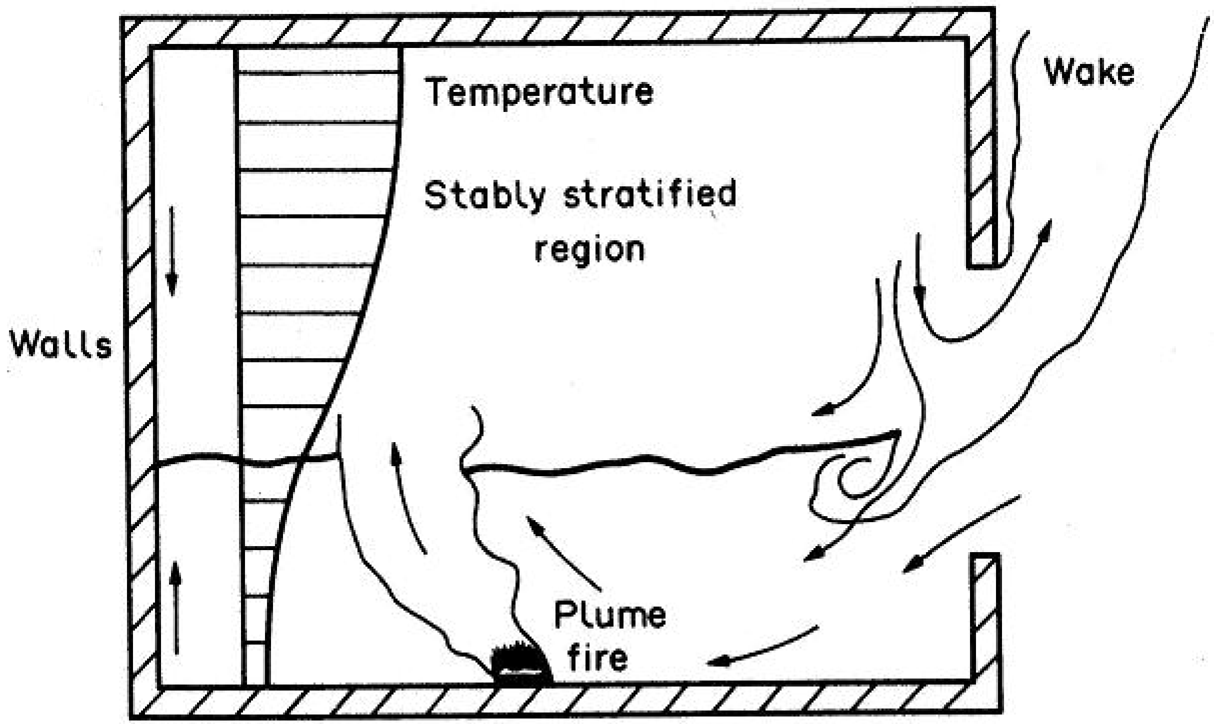


Fires

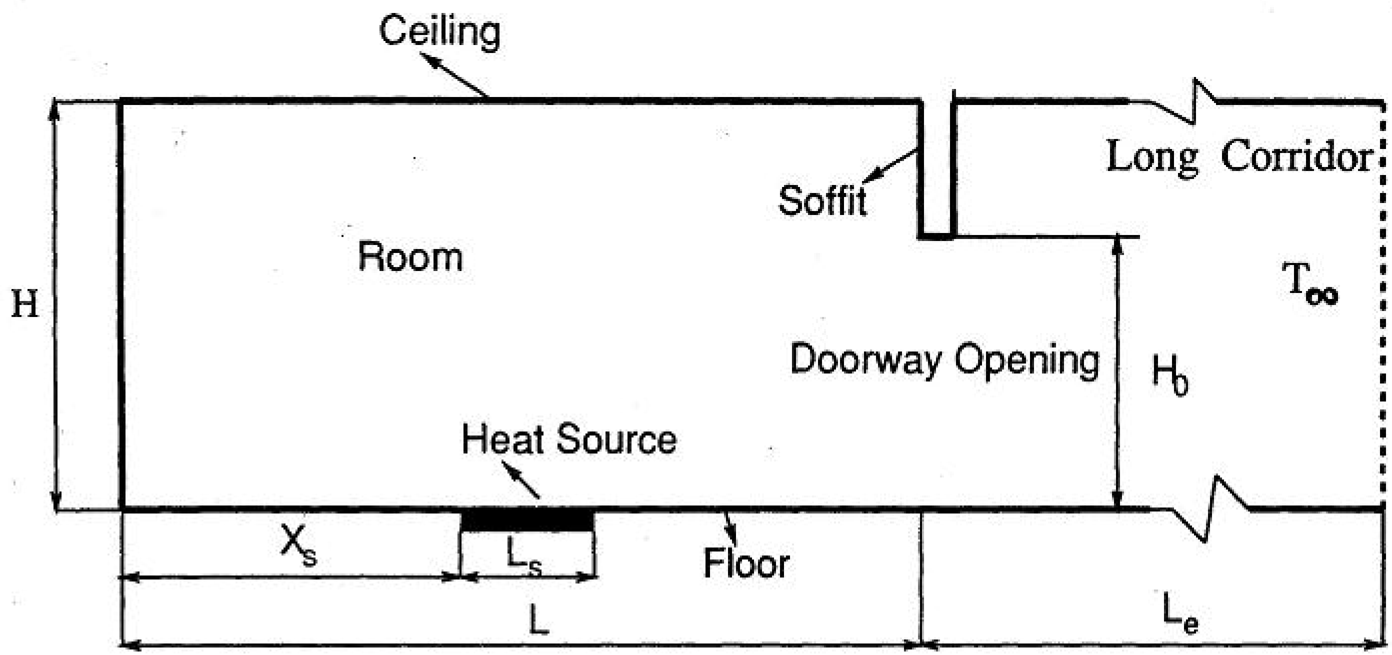
Buoyancy Effects in Fires

- Fire Growth
- Fire Spread to Other Objects
- Movement of Hot Gases, Smoke and Other Outputs
- Inflow of Oxygen to the Fire
- Removal of Combustion Products

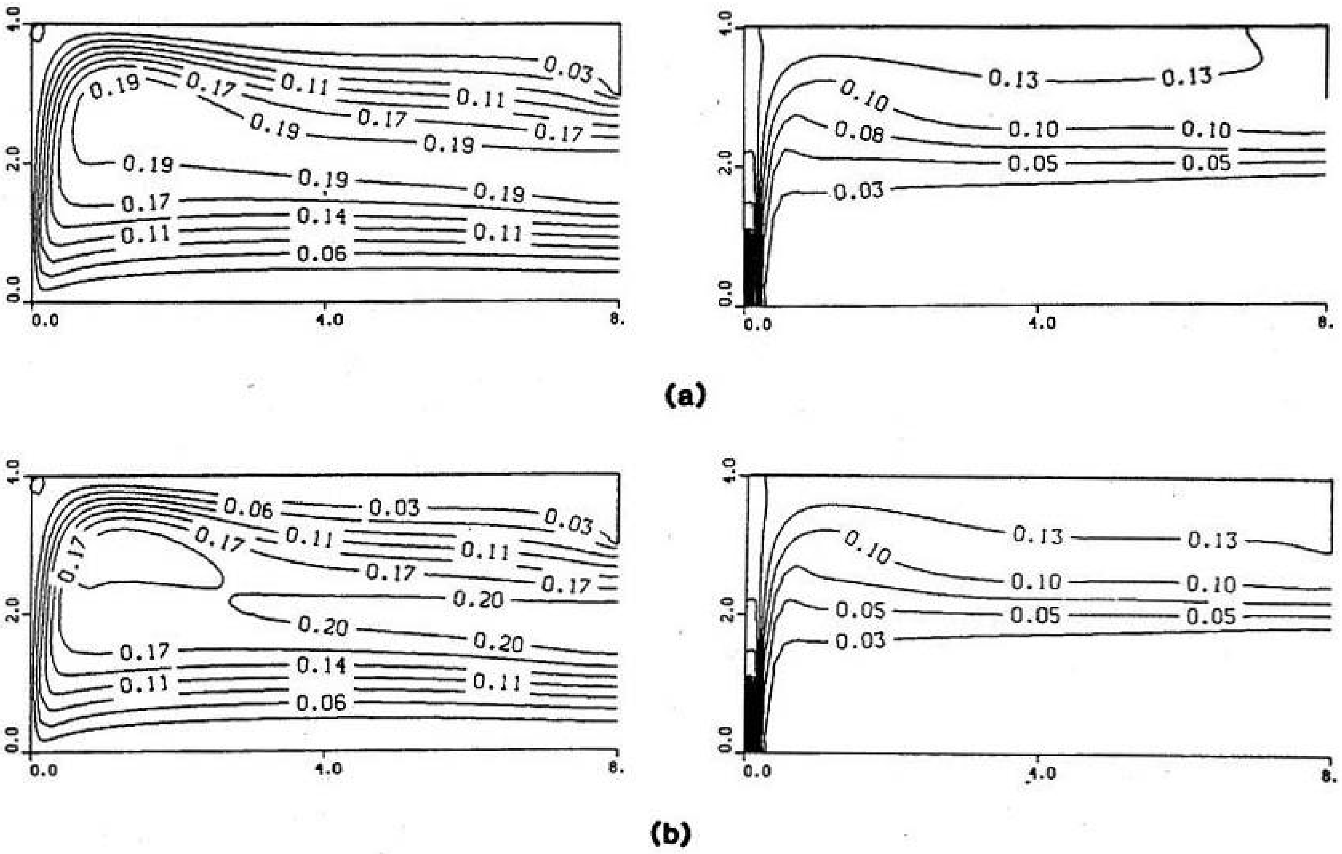
A Typical Room Fire



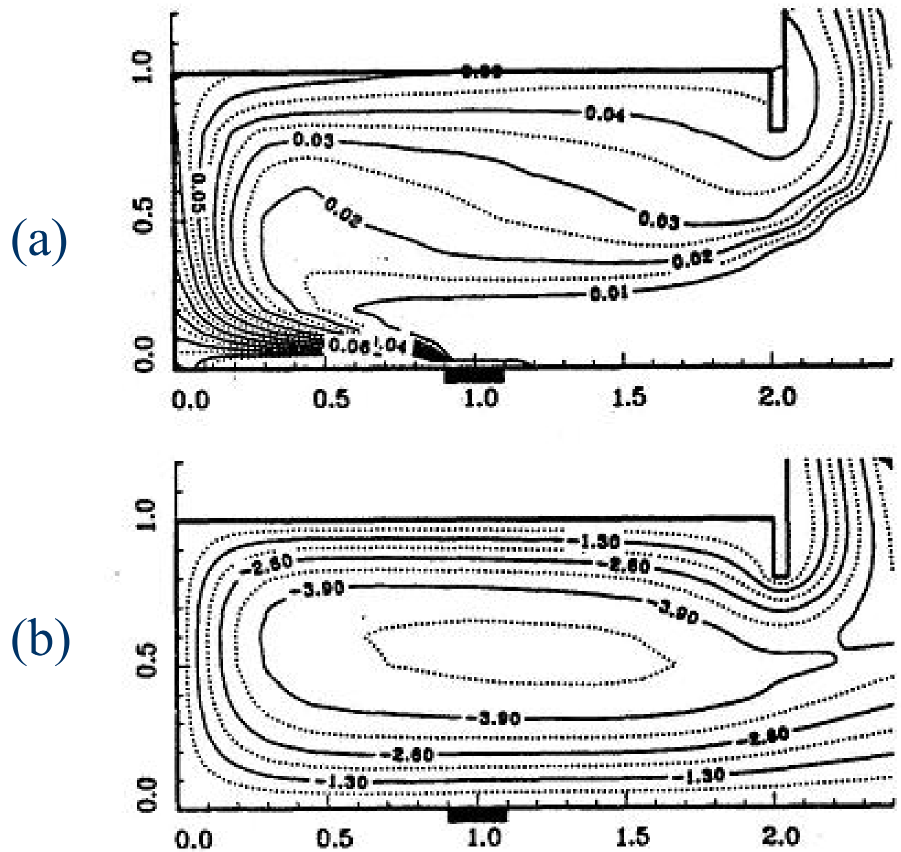
Room & Corridor System



Laminar Flow Generated by a Fire in a Room with an Opening

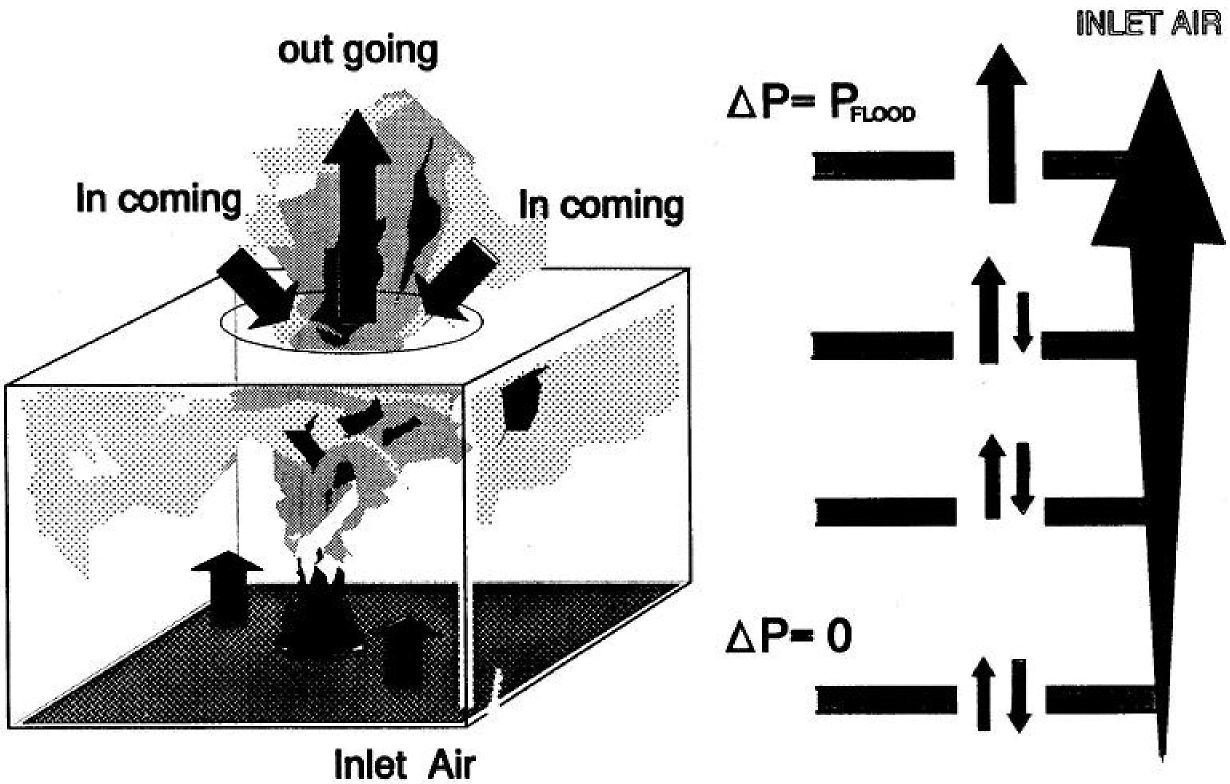


Flow and Thermal Fields for Turbulent Flow

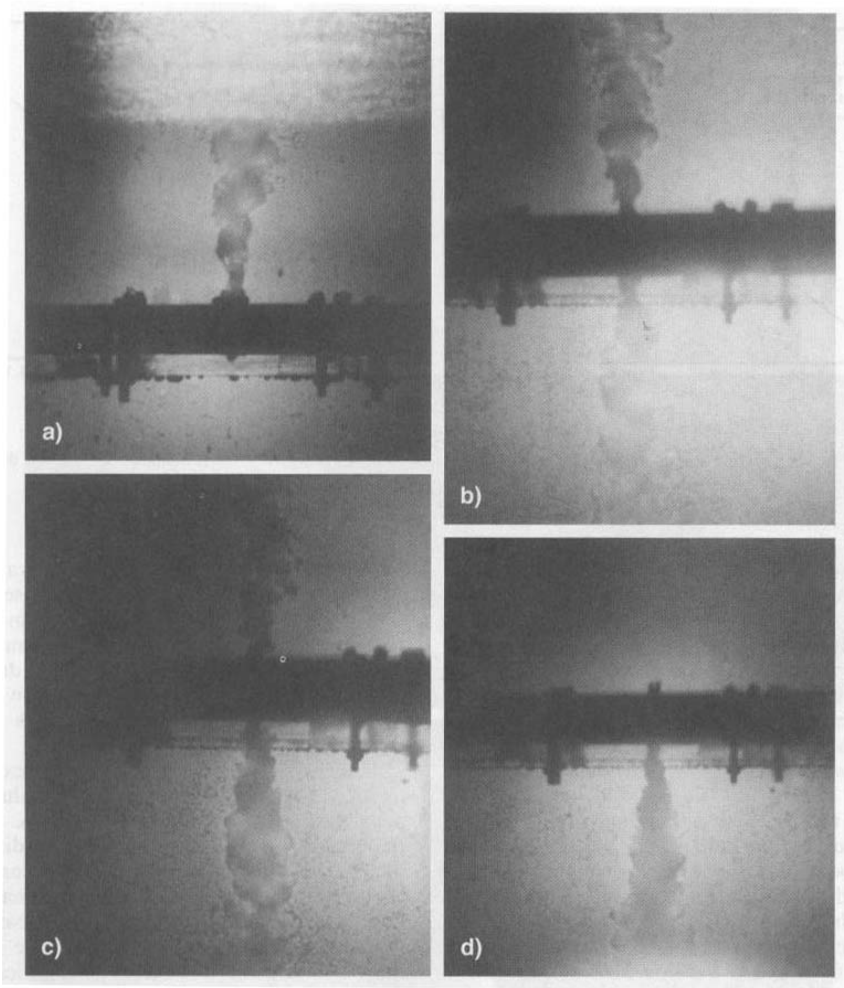


Steady state flow and thermal Field, (a) Isotherms and (b) Streamlines.

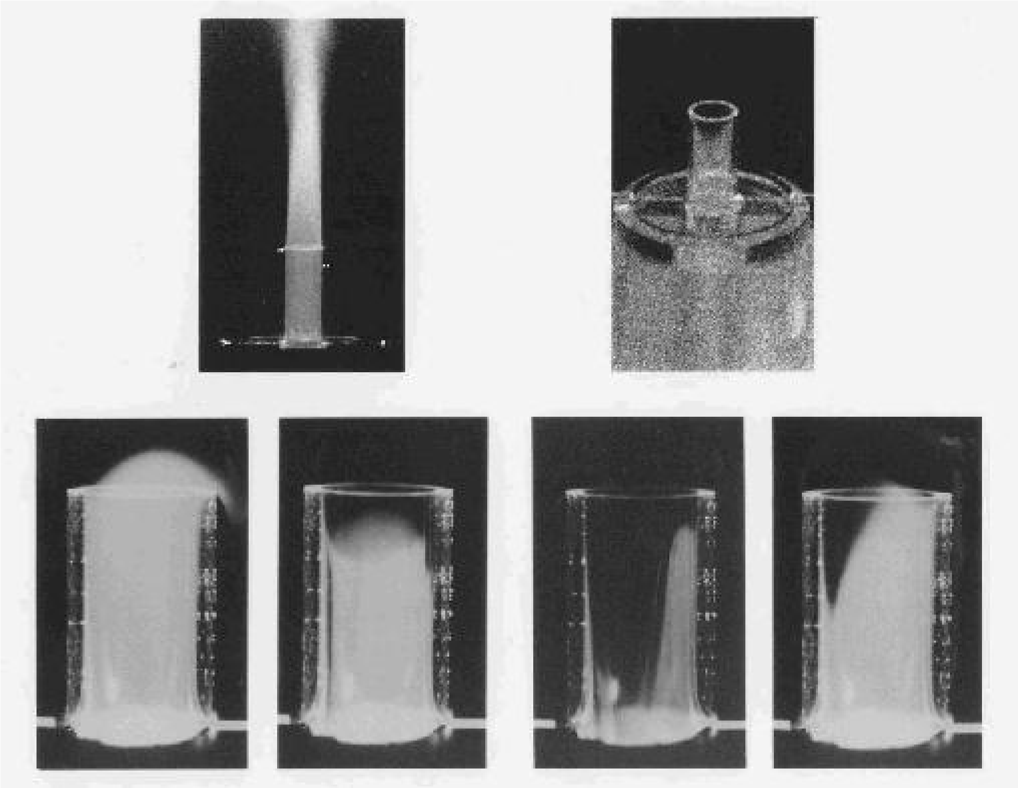
Flow in an Enclosure with a Single Horizontal Vent



Effect of Decreasing Pressure Difference with Fixed Density Difference Across a Vent in Water/Brine System



Flow Through a Horizontal Vent



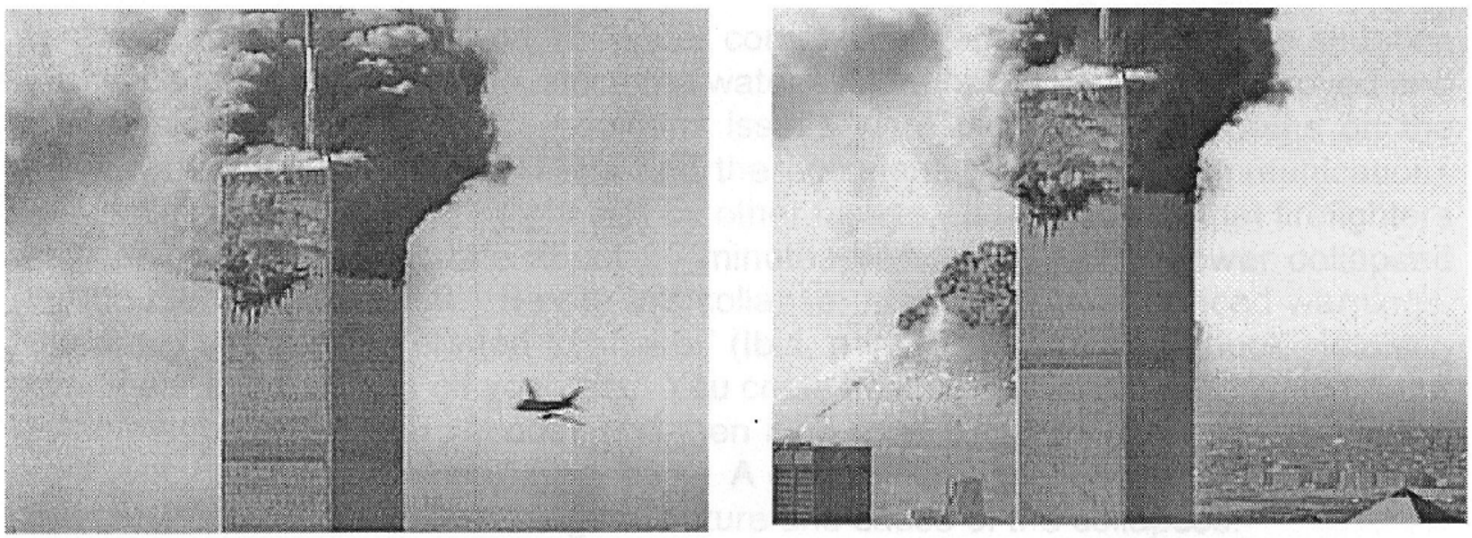
Safety and Security

Buoyancy-Induced Flow for Safety

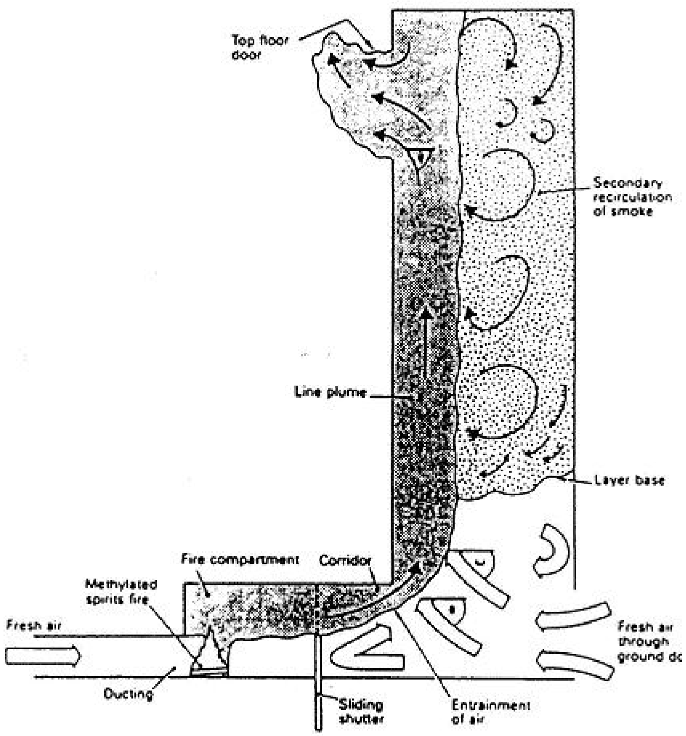
If Externally Induced Flow is Absent, Buoyancy-Driven Flow is the Only Mechanism for Energy Removal

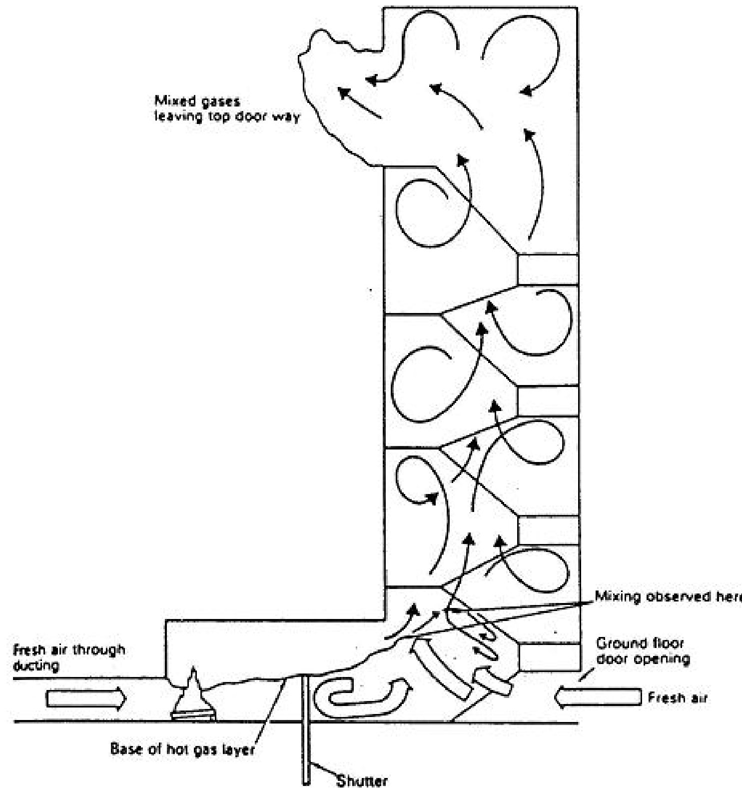
- Nuclear Safety
- Heat Removal from Electronic Systems
- Removal of Pollutants and Toxic Materials
- Natural Ventilation

World Trade Center Attacks



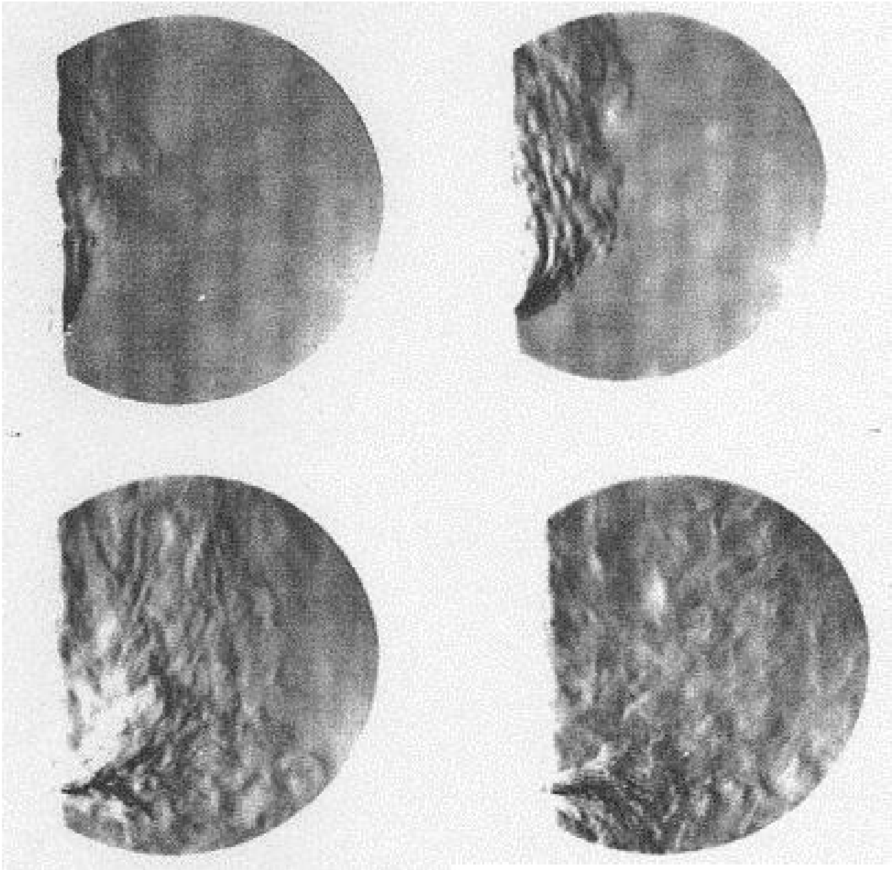
Flows in a Vertical Elevator Shaft and in a Stairwell



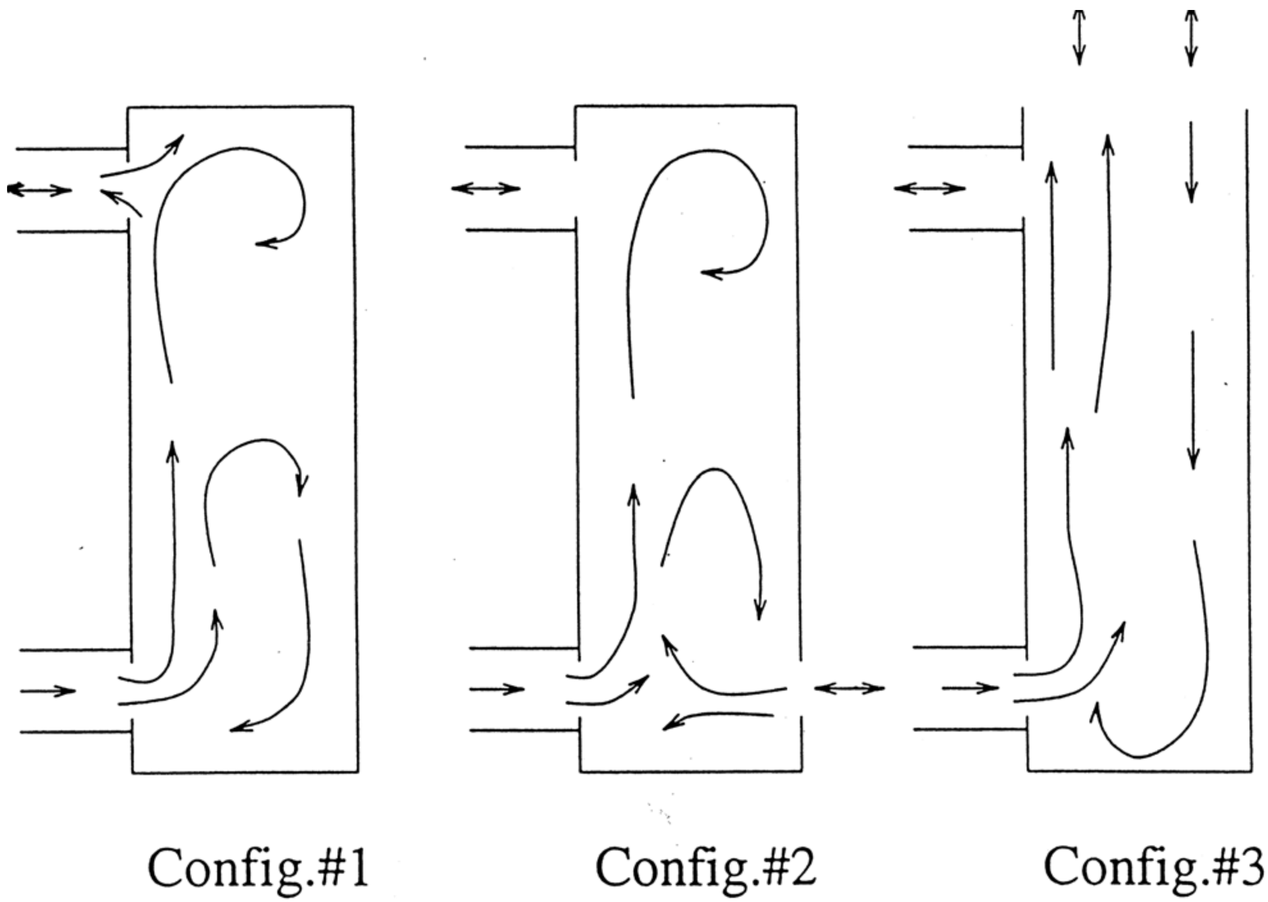


From Marshall (1986)

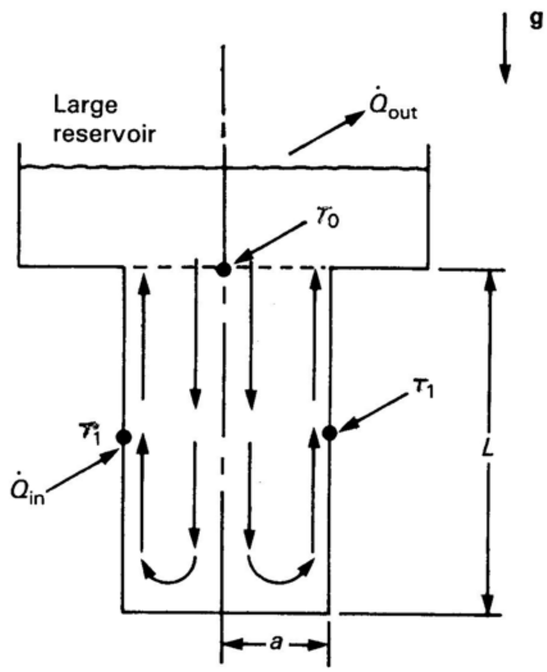
Series of Schlieren Photographs of the Buoyant Flow Near the Inlet of the Vertical Shaft, with Increasing Inlet Flow Rate from Left to Right and Down



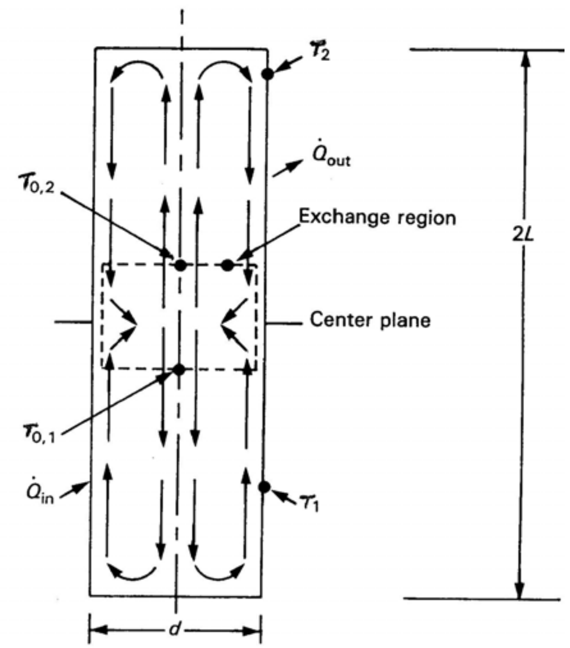
Typical Flows in a Vertical Elevator Shaft



Thermosyphons



Open Thermosyphon



Closed Thermosyphon

Cooling of Electronic Systems

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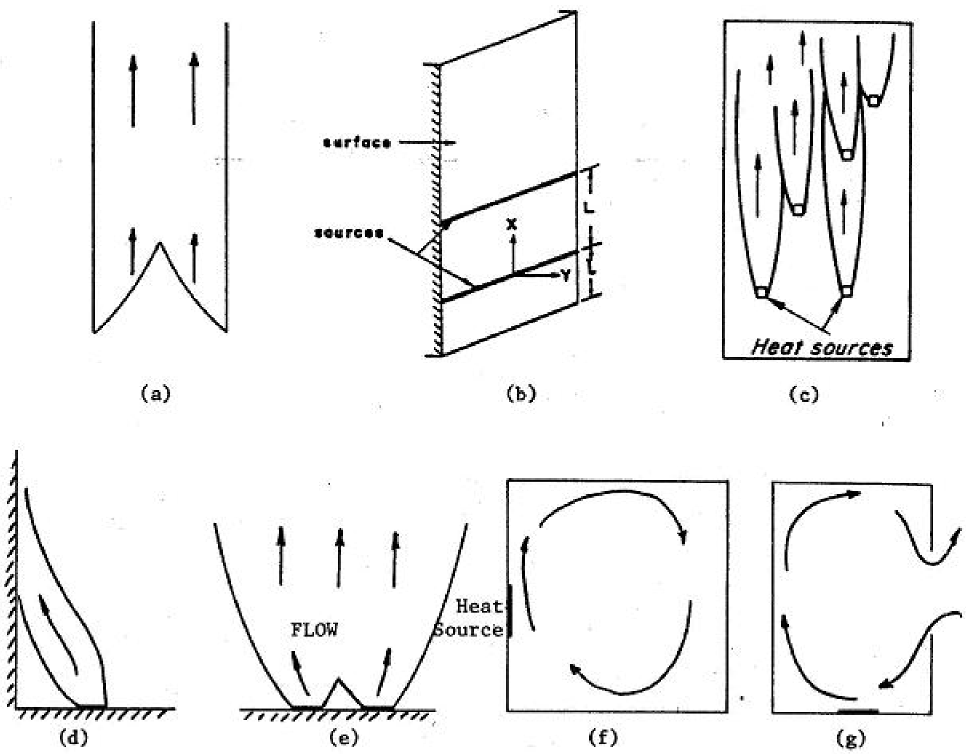
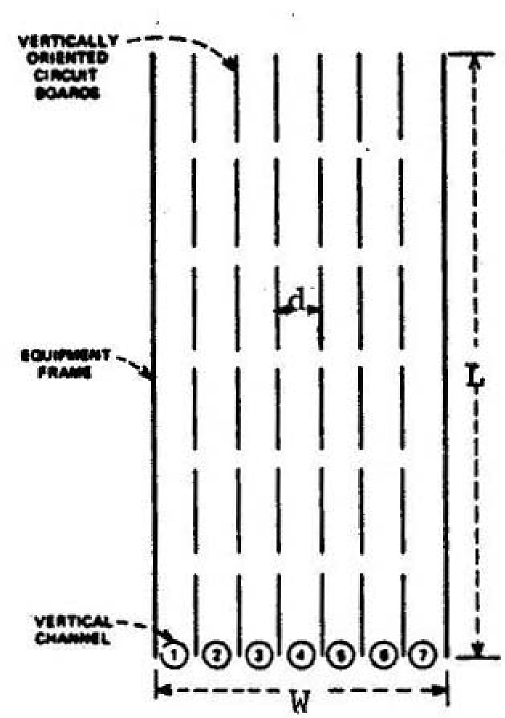
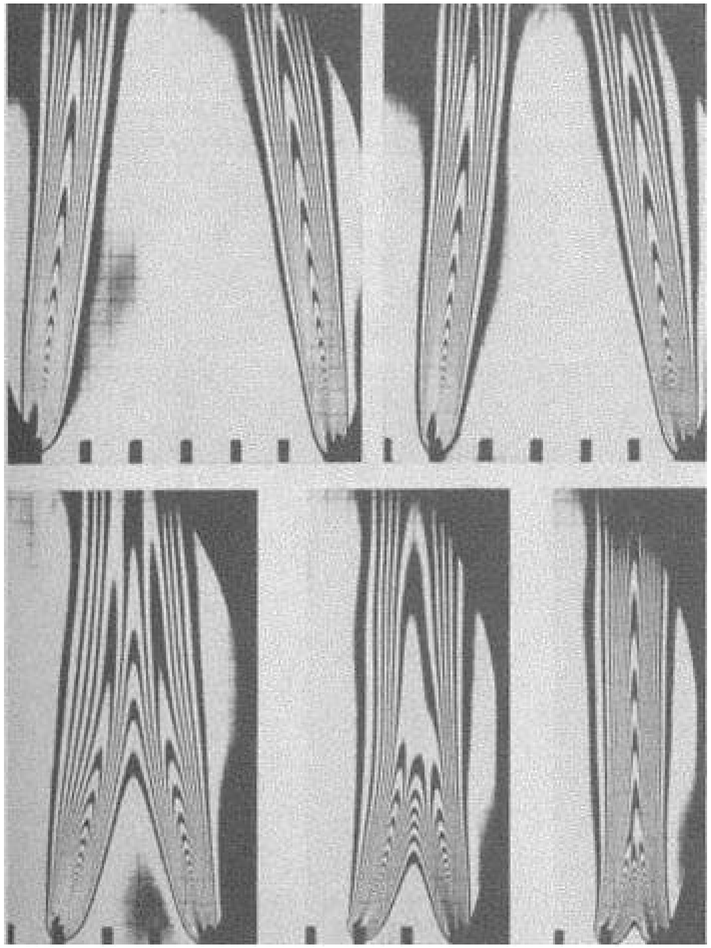
Natural Convective Cooling of Electronic Equipment



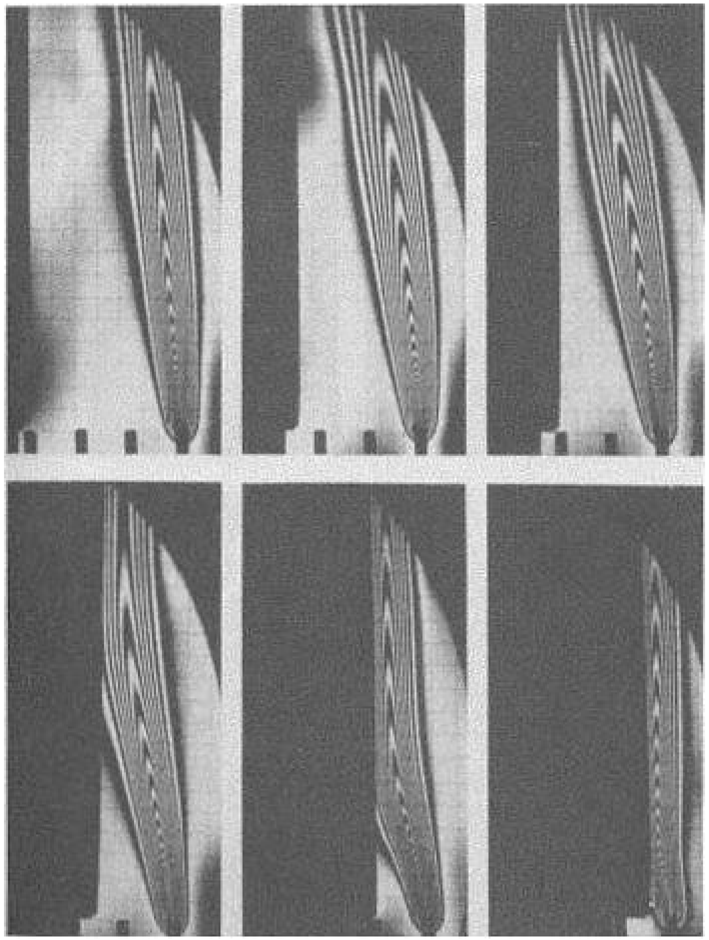


Interaction Between Adjacent Plane Plumes of Equal Strength in Air



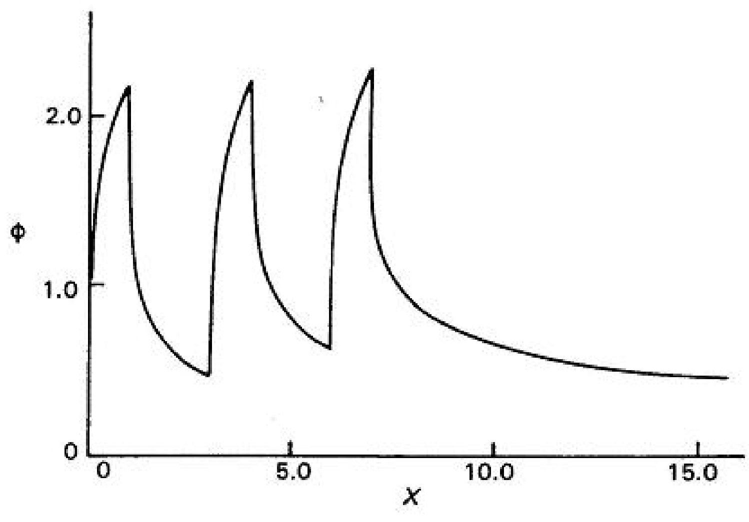
From Pera and Gebhart (1975)

Effect of a Vertical Wall on a Plane Plume Flow at Various Spacings

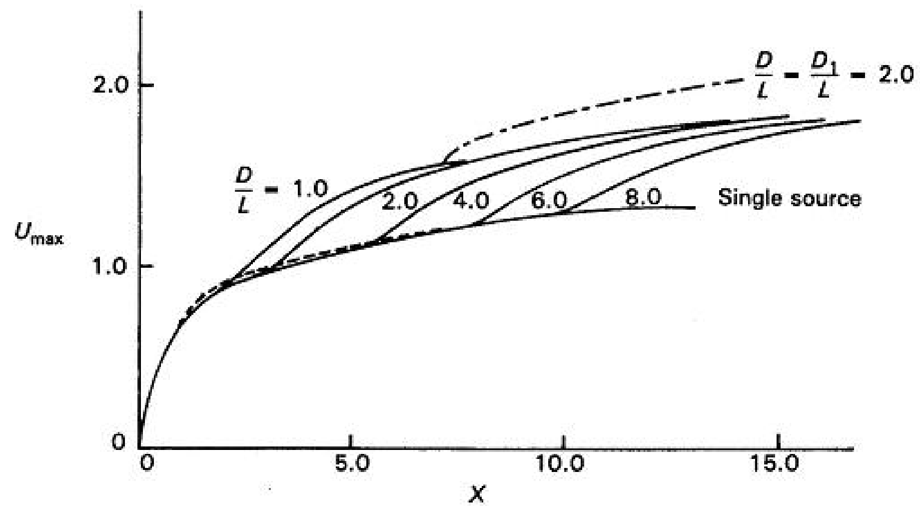


From Pera and Gebhart (1975)

Computed Downstream Variations of Dimensionless Surface Temperature and Maximum Velocity



(a)



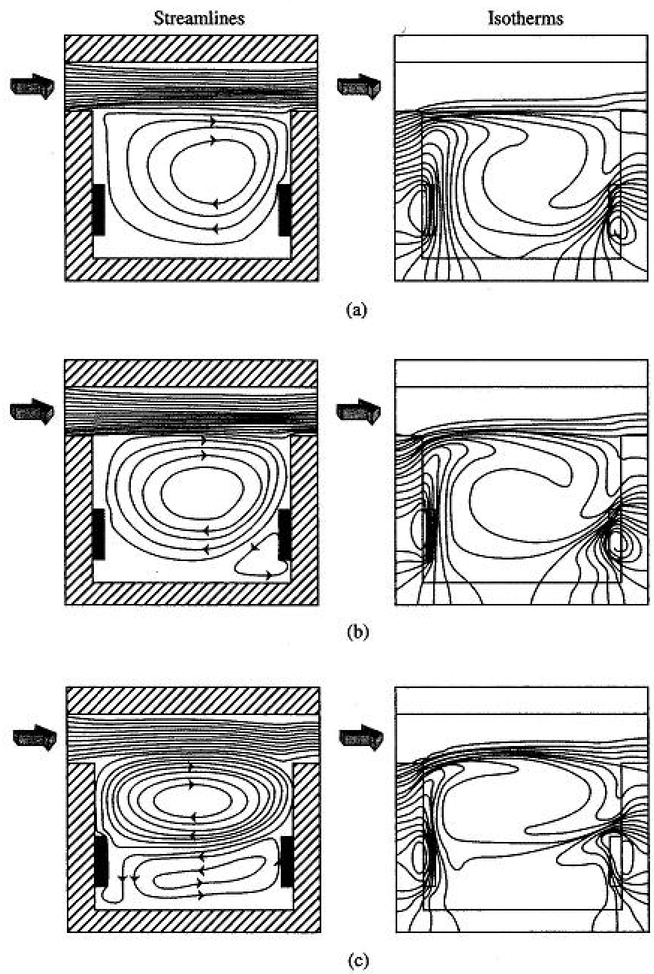
(b)

(a) Surface temperature variation for three heated elements for D/L=D/L=2.0

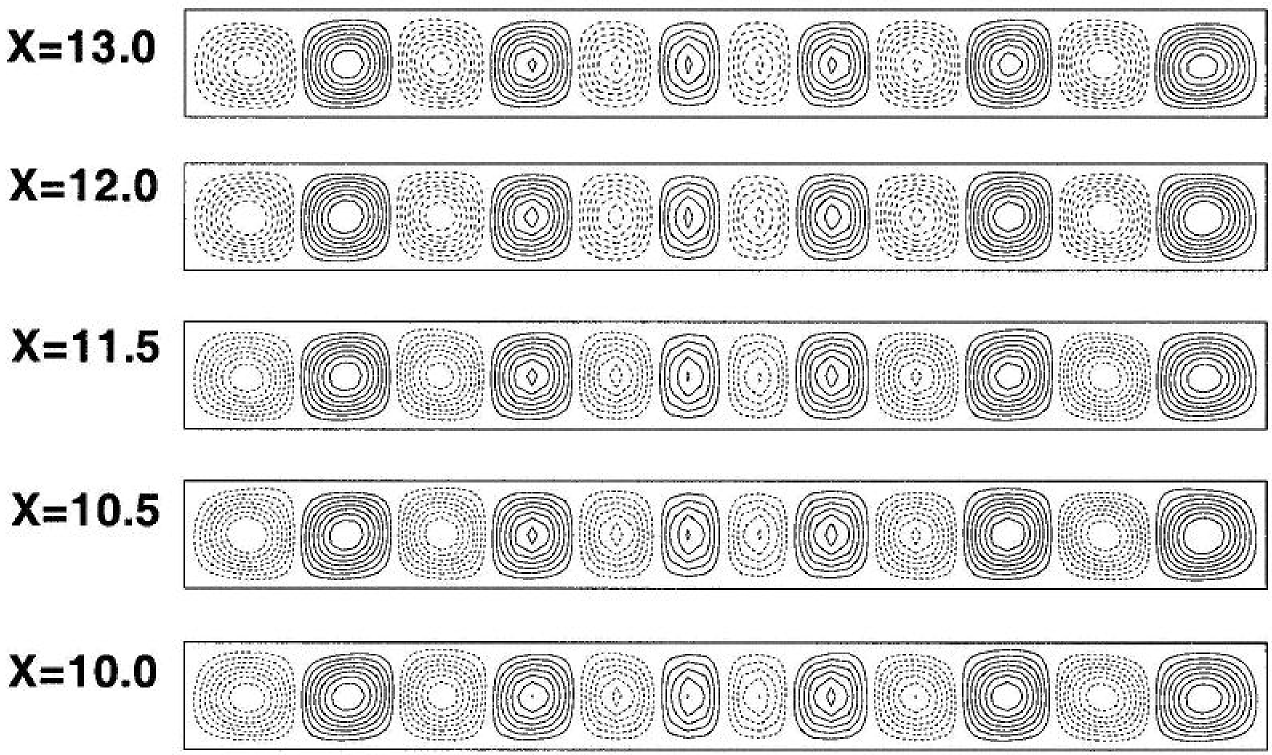
(b) Variation of U_{max} for various distances separating heated elements;

(—) two elements; (– _ –) three elements with D/L=D/L=2.0; (– –) single source

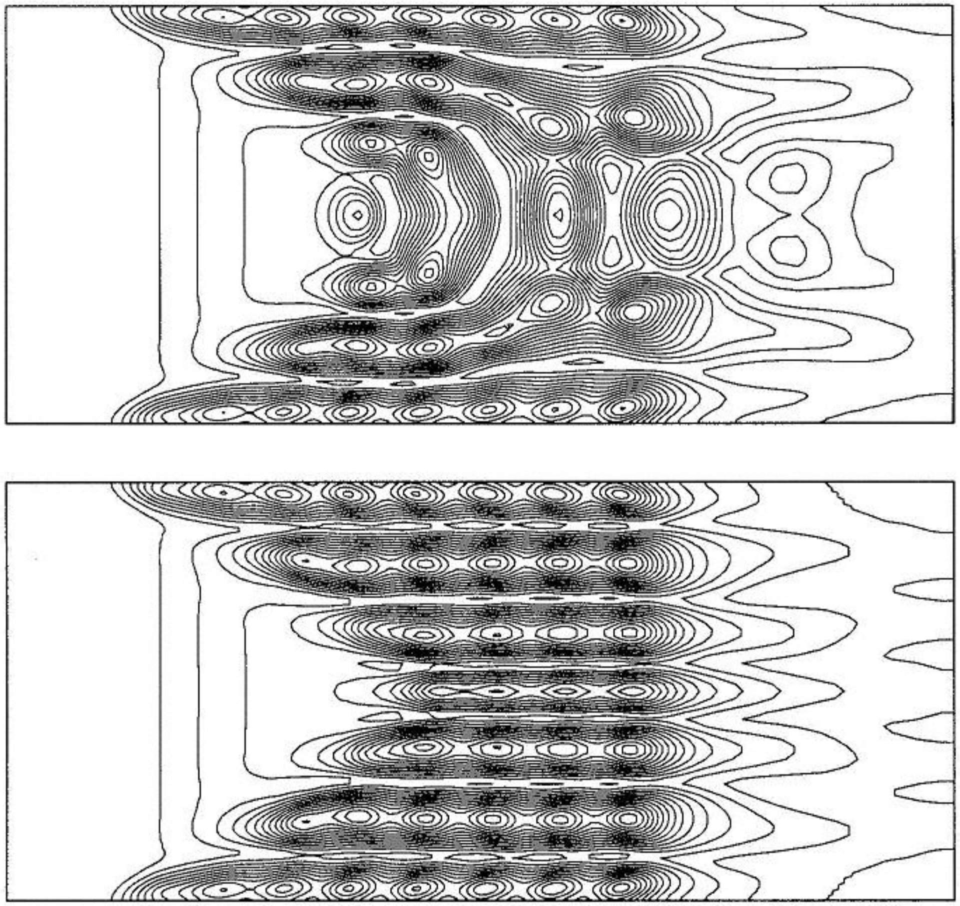
Flow in an Enclosure due to Isolated Heat Sources



Steady Streamlines on Y-Z Planes for 3D Flow in a Channel

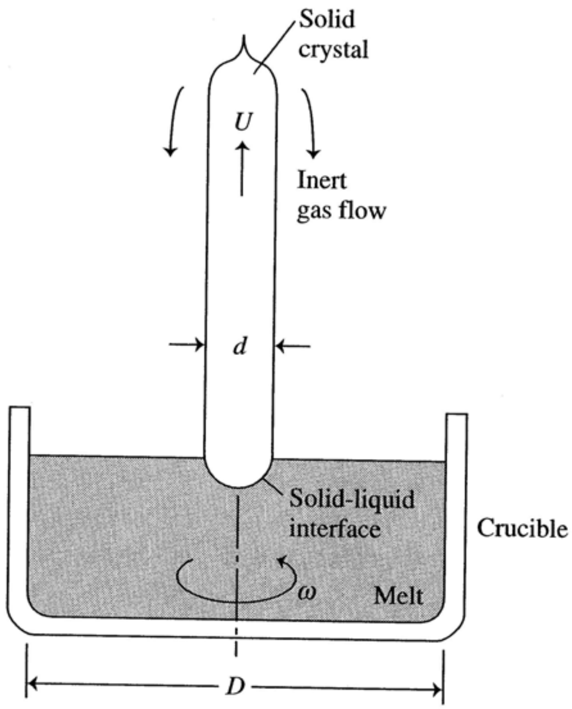


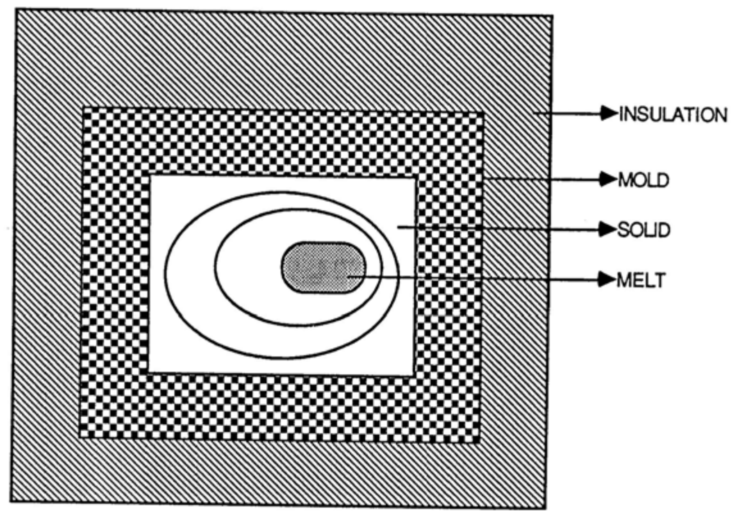
Isotherms on the Horizontal Midplane at τ=8.0 (Top Figure) and τ=24 (Bottom Figure) for Re=20, Gr=10000 and Ar=10.0



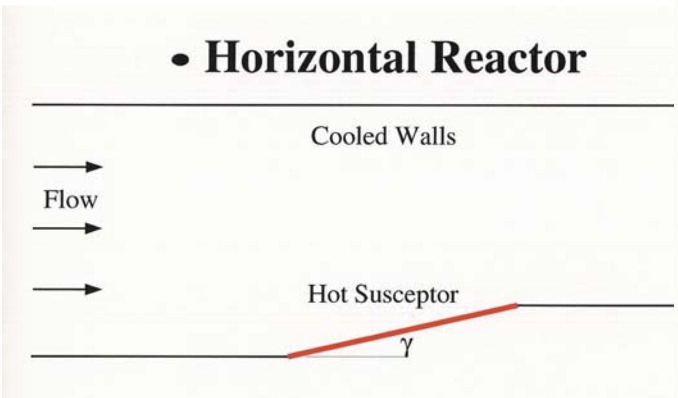
Materials Processing

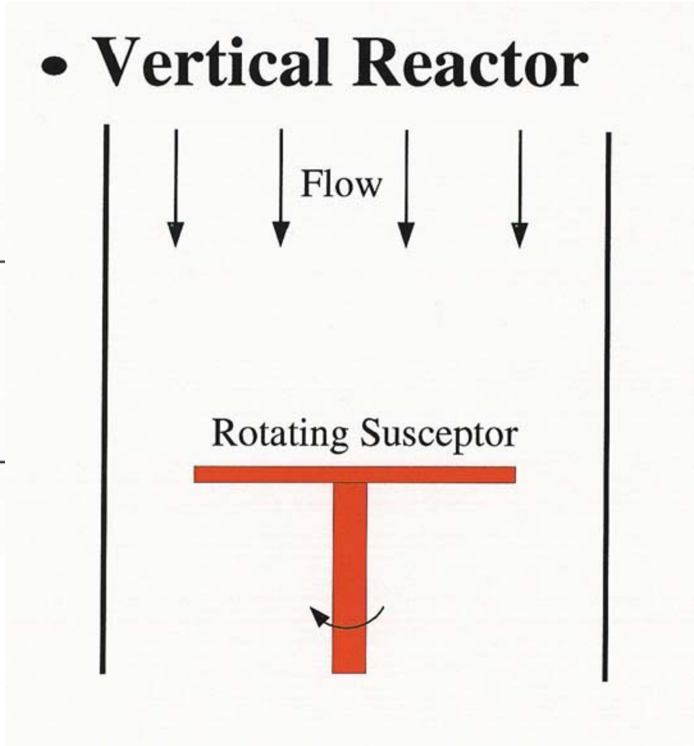
Czochralski Crystal Growing and Casting



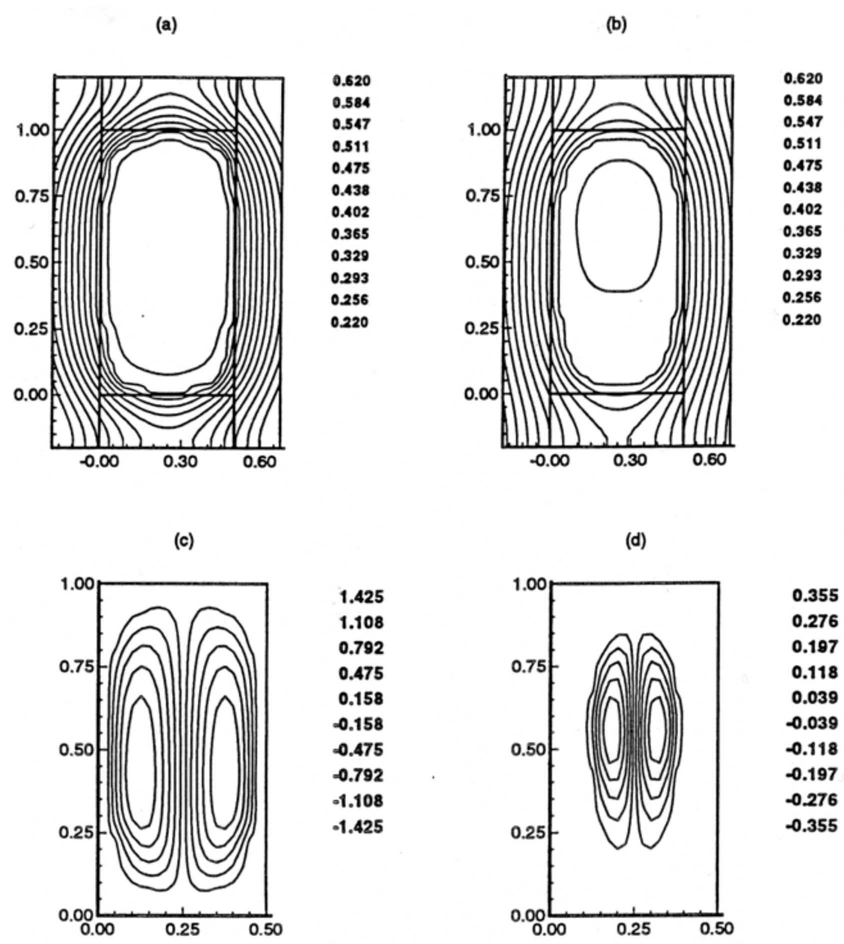


Chemical Vapor Deposition





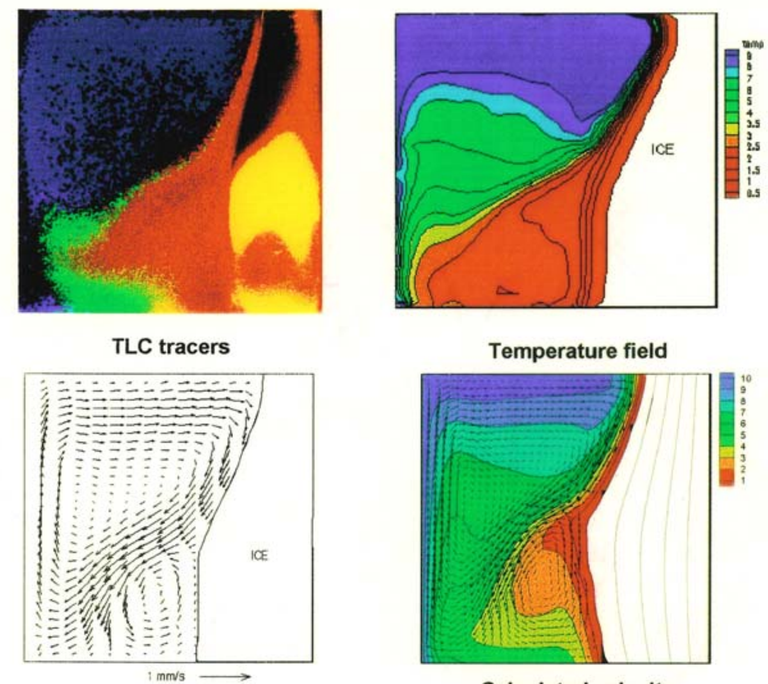
Solidification with Conjugate Transport at the Wall



Isotherms

Streamlines

Solidification of Water in an Enclosure with Conjugate Effects



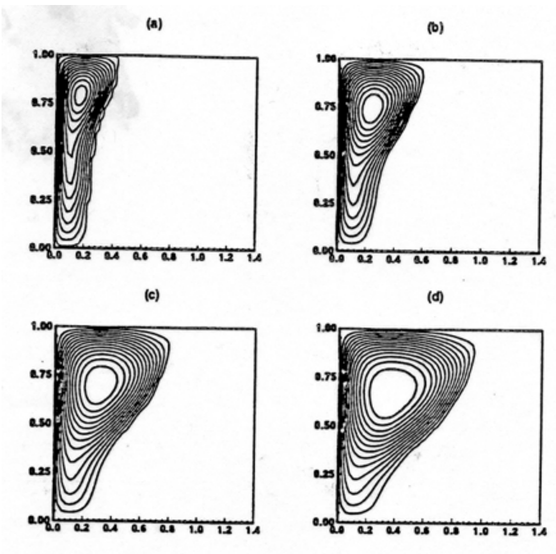
TLC tracers

Temperature field

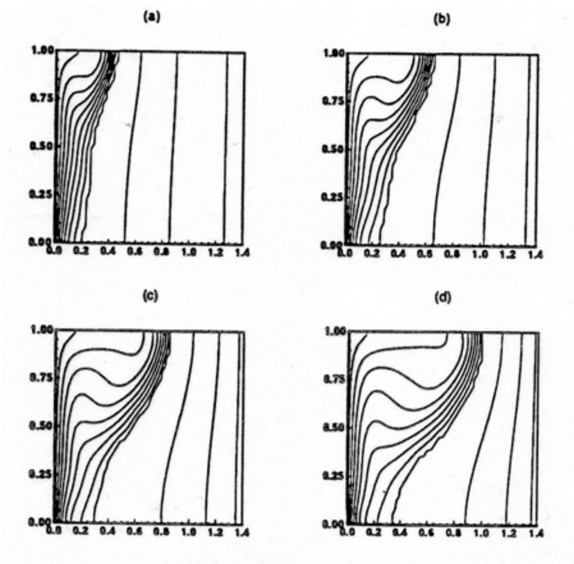
Evaluated velocity

Calculated velocity and temperature fields

Melting of Gallium in Enclosed Region

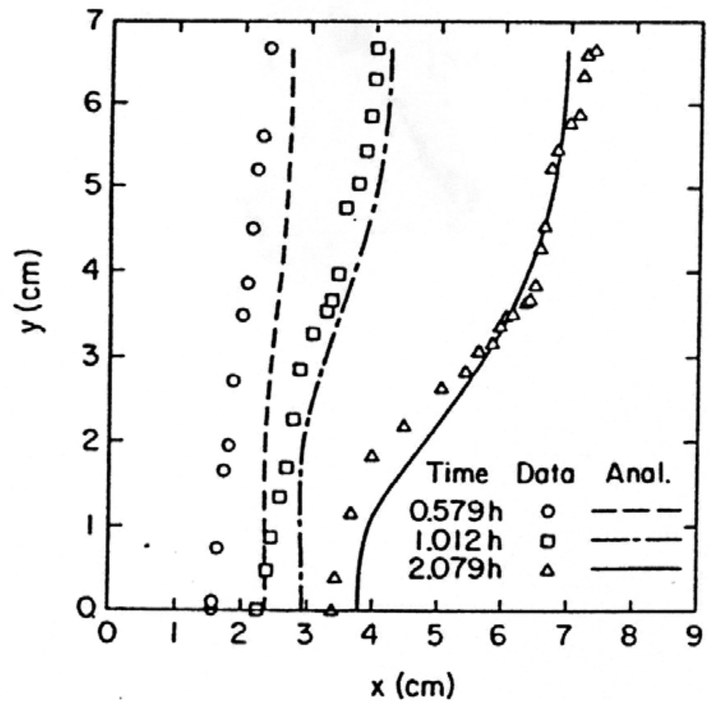


Streamlines



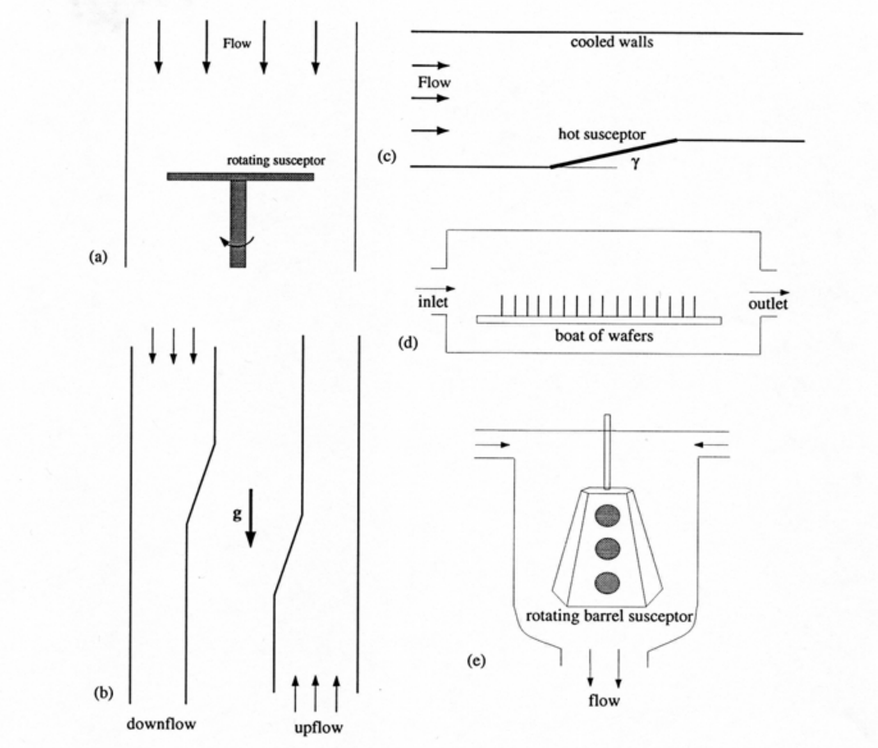
Isotherms

Measured Versus Calculated Solid-Liquid Interface in Solidification



From Wolff and Viskanta (1987)

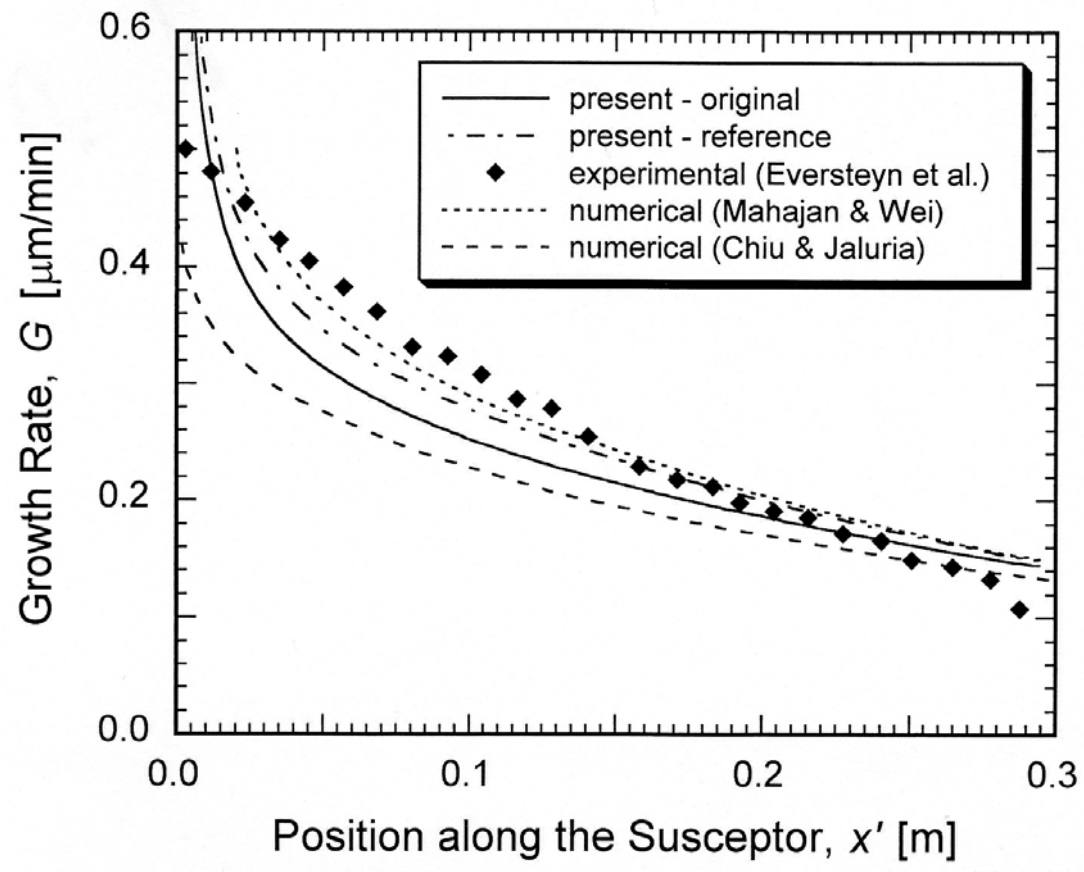
Sketch of Typical CVD Reactors



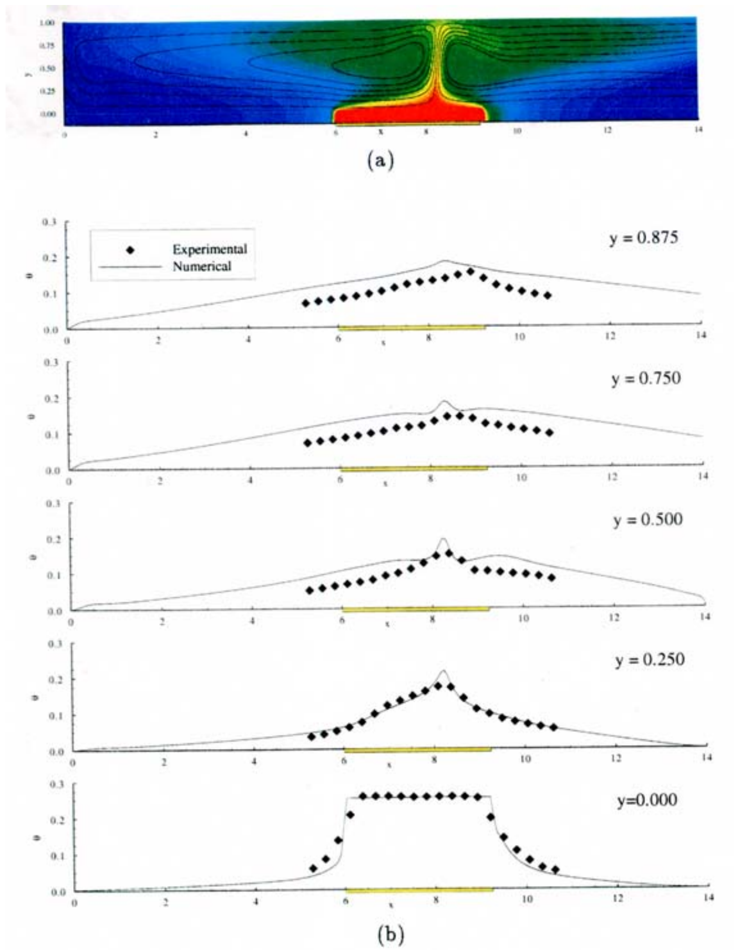
(a) Rotating (b) Vertical (c) Horizontal

(d) Tubular (e) Barrel

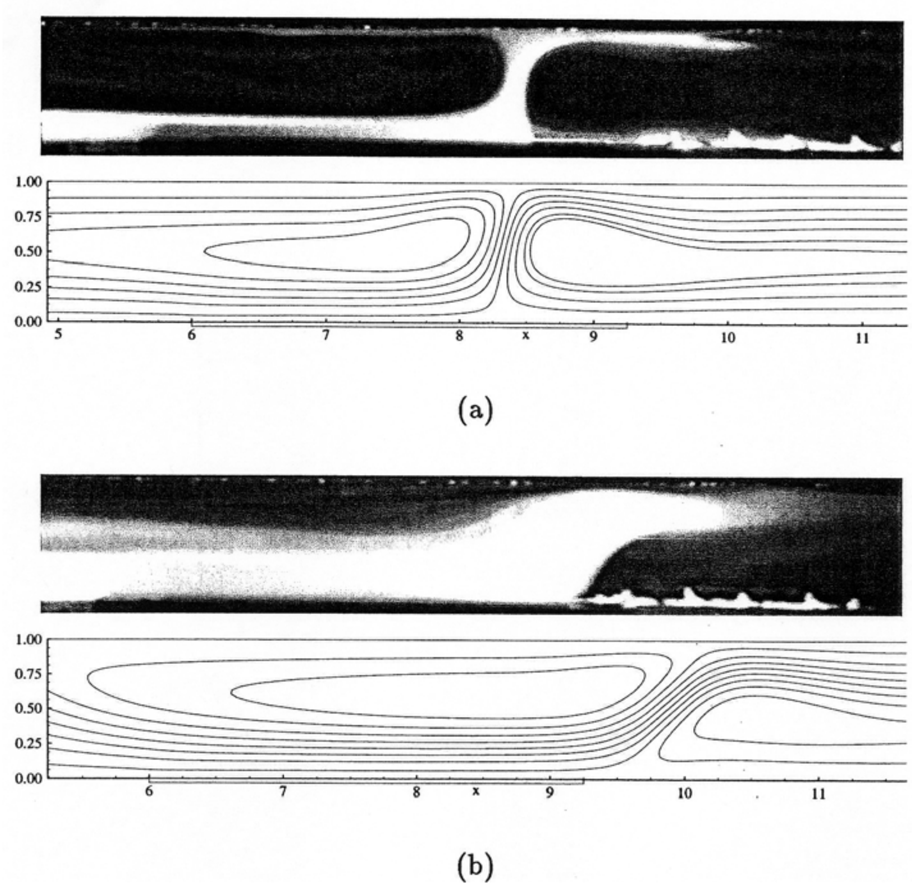
Film Growth in a Horizontal CVD Reactor



Flow and Temperature Fields in a Horizontal CVD System



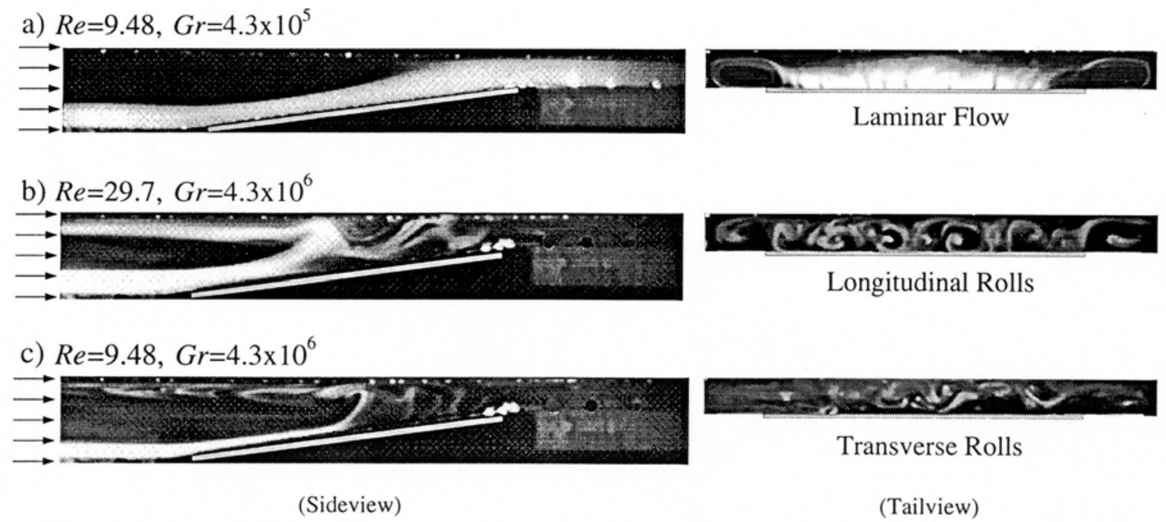
Experimental and Numerical Results on Horizontal Channel Flow for CVD



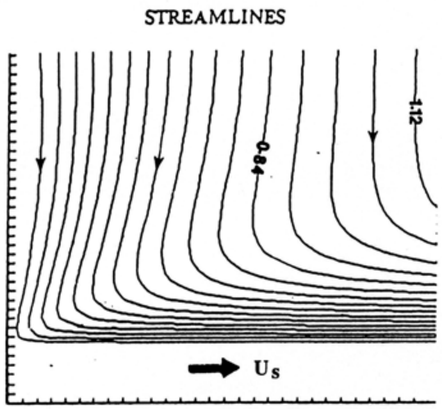
(a)

(b)

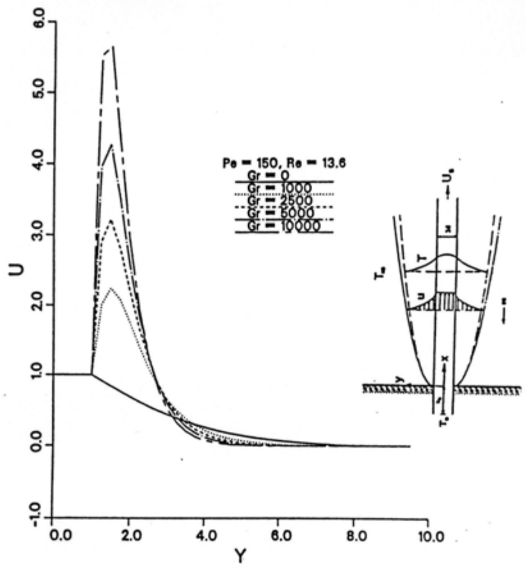
Flow Patterns in Horizontal Channel Flow for CVD



Flow Due to Moving Surface and Buoyancy

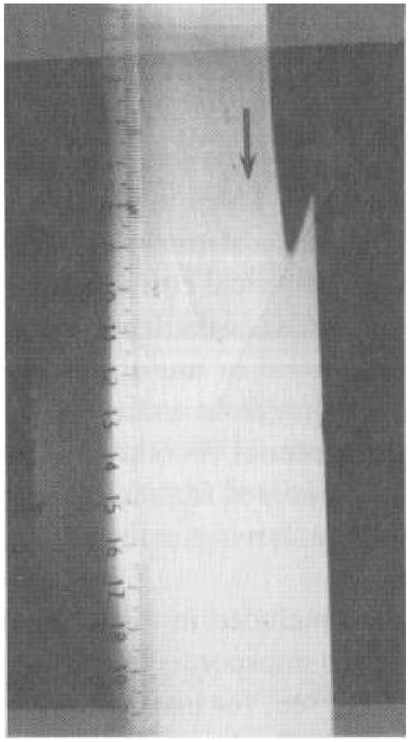


(a)



(b)

Sequence of Photographs Showing the Flow Near the Surface of the Aluminum Plate Moving Vertically Downward at U_s = 3.7 cm/s in water



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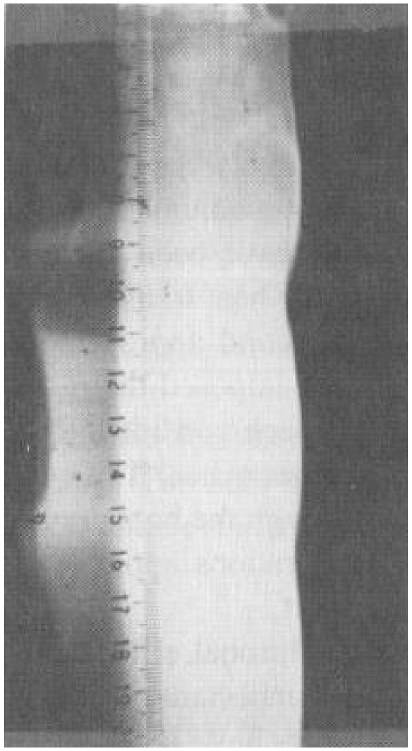

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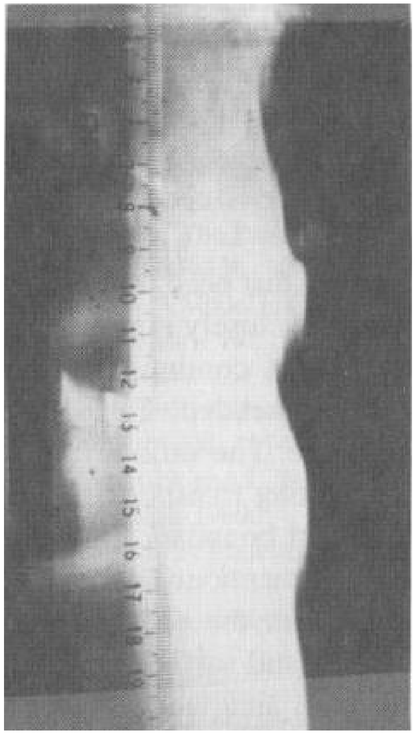

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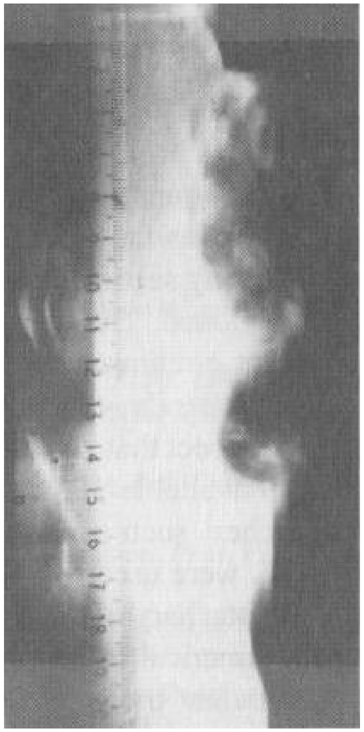

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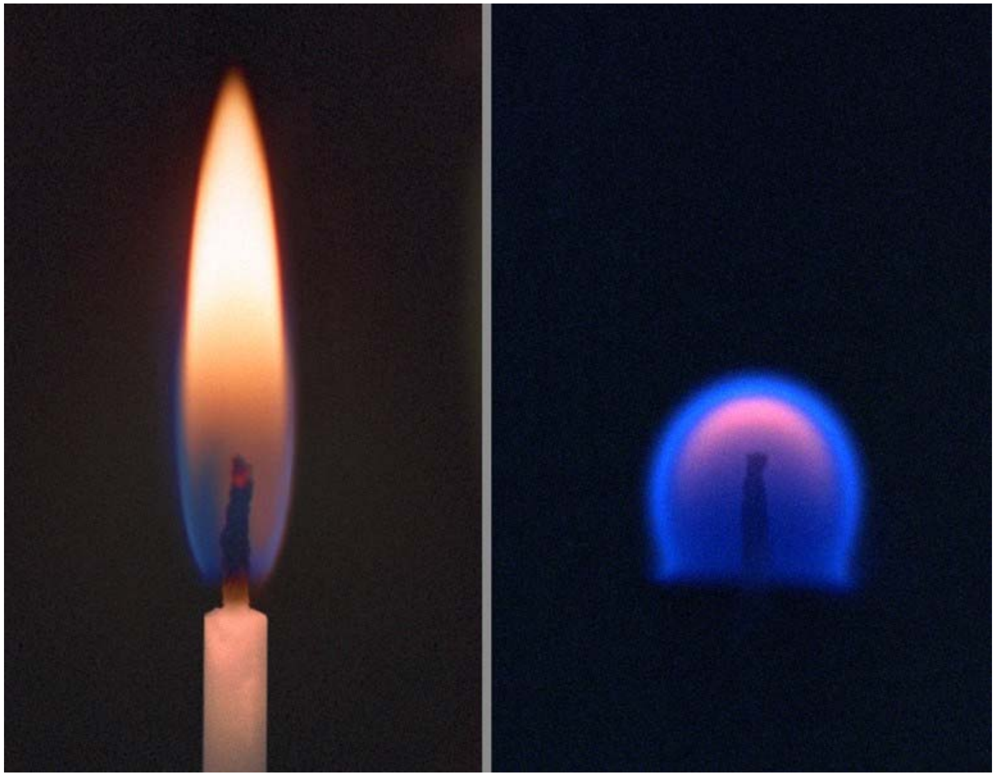
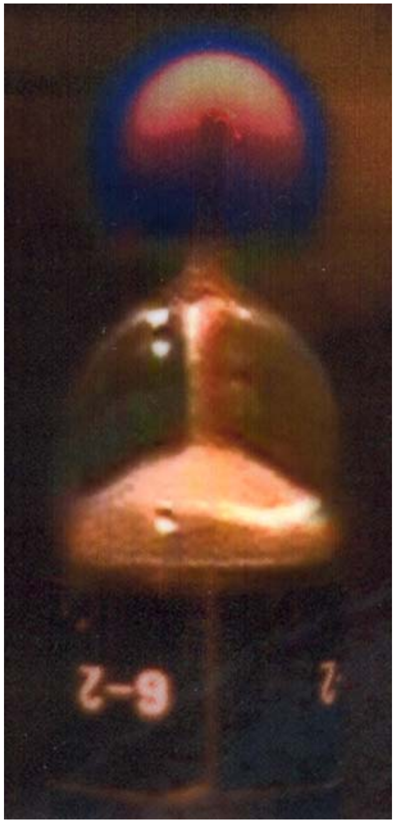
Microgravity Transport

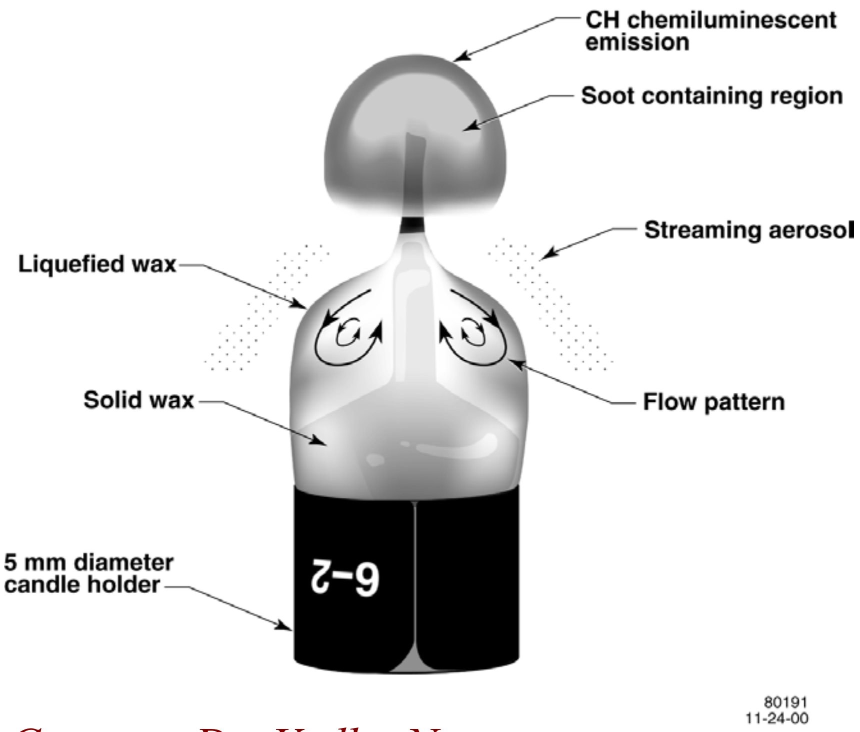
Candle Flame under Normal and Microgravity Conditions



Courtesy Dr. Vedha Nayagam

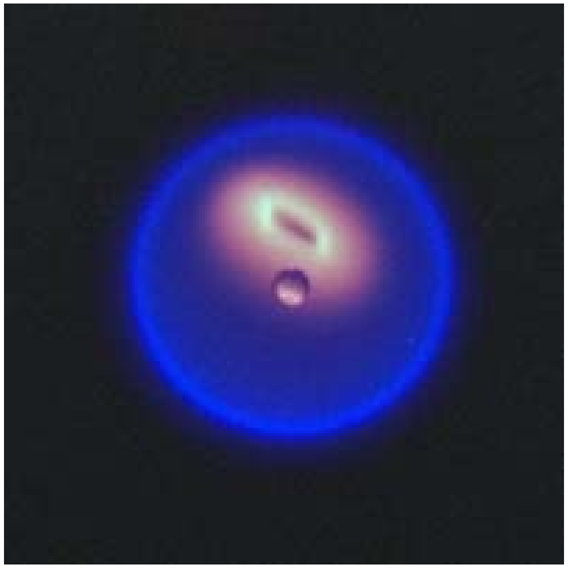
Liquefied Candle Flame under Microgravity





Courtesy Dr. Vedha Nayagam

Burning Droplet under Microgravity and Normal Gravity



Spherically symmetric burning of a heptane droplet in microgravity (left), and a fiber suspended heptane droplet burning in air at normal gravity (right). Buoyancy forces in normal gravity leads to elongation of the flame destroying the spherical symmetry and making theoretical models complex.

Courtesy Dr. Vedha Nayagam

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Conclusions and Future Research Needs

Conclusions

- Buoyancy-Induced Flows Arise in a Wide Range of Basic and Applied Problems
- Only Mechanism in the Absence of External Flow
- Underlying Mechanism for Several Natural Phenomena
- Critical for Heat and Material Rejection
- Can Affect Quality of Processed Materials
- Extremely Important in Safety and Security
- Provides Baseline Transport Rates
- Can be Used Effectively to Simplify System Design

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Future Research Needs

- Need Better Link Between Basic Research and Engineering Practice
- Experimentation for Validation and Insight
- Natural Processes in Oceans, Lakes, Environment
- Mantle Convection, Geothermal Energy
- Microgravity Transport
- Fire Growth, Forest Fires, Building Fires
- Natural Ventilation, Thermosyphons

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Future Research Needs

- **Different Scales: Micro, Nano, Global**
- **Multiphase and Multispecies Transport**
- **Effect of Buoyancy-Driven Flows on Materials Processing**
- **Environmental Effects of Heat and Mass Rejection**
- **Low Grashof Number Flows, Strong Property Changes**
- **Combined Mechanisms**

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