2003 Robert Henry Thurston Lecture

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2003 ASME IMECE
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Lecture encourages stimulating thinking on a subject of broad technical interest to engineers
2003 ASME Thurston Lecture
November 19, 2003, Washington, D. C.

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Buoyancy-Induced Flows
in Nature and in Technology
Recognized for:

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

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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

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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) 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

(a) $\gamma = 45^\circ$

(b) $\gamma = 90^\circ$

(c) $\gamma = 135^\circ$

Isotherms

Streamlines
Basic Mechanisms
Buoyancy Force

Region of lower density, $p(\tau, C, \rho)$

Quiescent ambient medium for which $\rho_a = p(\tau_a, C_a, \rho_a)$

$g$—Gravitational force

$B(x, y)$

$\frac{\partial p}{\partial x} = \rho g$

$- \frac{dp_a}{dx} = g\rho_a$

$\frac{dp_a}{dx} > \frac{\partial p}{\partial x}$ if $\rho_a > \rho$
Buoyancy Term

\[ p = p_a + p_m \]

Pressure \hspace{1em} Hydrostatic Pressure \hspace{1em} Motion Pressure

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

= Buoyancy – Pressure Gradient

Convection Velocity

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

\[ u = O(\sqrt{g \Delta \rho L / \rho}) \]

Boussinesq Approximation

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

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

\[ \nu = \text{kinematic viscosity} \]

Reynolds Number, \( Re \approx \sqrt{Gr} \)
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

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

(a) Plume

(b) Thermal

(c) Starting plume

(d) Jet
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

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.

From Carey and Gebhart (1981)
Variation of Water Density with Temperature

\[ B > 0, \text{ upflow} \]

Region of convective inversion

Local buoyancy force reversal

Outside reversal

Inside reversal

\[ B < 0, \text{ downflow} \]

\[ \rho(t, 1) \]

\[ B = g(\rho - \rho) \]

\[ \tau(\circ C) \]

\[ \tau_0 \]

\[ a \]

\[ b \]

\[ c \]

\[ d \]

\[ e \]

\[ f \]
Qualitative Sketch of the Stratification Cycle of a Water Body
Temperature Distributions in a Stratified Water Body

(a) Spring
(b) Summer
(c) Autumn

Depth (m)

Temperature (°C)

Theoretical
Measured
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
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)
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

- Temperature
- Stably stratified region
- Walls
- Wake
- Plume 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

IfExternally 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

Config.#1

Config.#2

Config.#3
Thermosyphons

Open Thermosyphon

Closed Thermosyphon
Cooling of Electronic Systems
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) Surface temperature variation for three heated elements for D/L=D/L=2.0
(b) Variation of $U_{\text{max}}$ 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

\[ X = 13.0 \]

\[ X = 12.0 \]

\[ X = 11.5 \]

\[ X = 10.5 \]

\[ X = 10.0 \]
Isotherms on the Horizontal Midplane at $\tau=8.0$ (Top Figure) and $\tau=24$ (Bottom Figure) for $Re=20$, $Gr=10000$ and $Ar=10.0$
Materials Processing
Czochralski Crystal Growing and Casting
Chemical Vapor Deposition

- Horizontal Reactor
  - Cooled Walls
  - Flow
  - Hot Susceptor

- Vertical Reactor
  - Flow
  - Rotating Susceptor
Solidification with Conjugate Transport at the Wall

Isotherms

Streamlines
Solidification of Water in an Enclosure with Conjugate Effects
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

![Graph showing growth rate vs position along the susceptor](image-url)
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

a) $Re=9.48, \ Gr=4.3\times10^4$

Laminar Flow

b) $Re=29.7, \ Gr=4.3\times10^6$

Longitudinal Rolls

c) $Re=9.48, \ Gr=4.3\times10^6$

Transverse Rolls

(Sideview)  (Tailview)
Flow Due to Moving Surface and Buoyancy
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
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
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
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
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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