Modelling and Monitoring of Coastal Marine Processes

Modelling and Monitoring of Coastal Marine Processes

Edited by

C.R. Murthy
Environment Canada, National Water Research Institute
Burlington, Ontario, Canada

P.C. Sinha
Indian Institute of Technology
New Delhi, India

Y.R. Rao
Environment Canada, National Water Research Institute
Burlington, Ontario, Canada

Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN 978-1-4020-8326-6 (HB)
ISBN 978-1-4020-8327-3 (e-book)

Copublished by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands
with Capital Publishing Company, New Delhi, India.

Sold and distributed in North, Central and South America by Springer,
233 Spring Street, New York 10013, USA.

In all other countries, except India, sold and distributed by Springer, Haberstrasse
7, D-69126 Heidelberg, Germany.

In India, sold and distributed by Capital Publishing Company,
7/28, Mahaveer Street, Ansari Road, Daryaganj, New Delhi, 110 002, India.

www.springer.com

Printed on acid-free paper

Printed in India.

Foreword

The majority of personnel responsible for coastal zone management and coastal environmental impact analysis are drawn mainly from traditional fields of physical, biological and engineering sciences. Many of them are not exposed to specialized training in dealing with complex problems of the coastal zone. Therefore, there is a growing need for trained marine professionals in countries of the central Indian Ocean (IOCINDIO) region to deal with the coastal marine pollution and related issues arising out of accelerated developmental activities. Modelling and Monitoring of Coastal Marine Processes (MAMCOMP) was first initiated by the UNESCO's Intergovernmental Oceanographic Council (IOC) for the IOCINDIO region in 1994 as a training programme in Integrated Coastal Area Management (ICAM). It has been successfully conducted every year, with the exception of 1998, at Indian Institute of Technology Delhi, India. Recognizing the growing need for trained marine professionals in the Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area (RSA) to deal with emerging marine pollution, and other related issues arising out of accelerated land-based and offshore developmental activities at the third session of the IOCINDIO region meeting during 2000 in Tehran, I.R. of Iran, it was decided to conduct the MAMCOMP-ICAM training programme in the RSA region in collaboration with the ROPME. The IOC and ROPME in co-operation with the UAE Federal Environmental Agency and UAE University conducted MAMCOMP-2001 at Al Ain, UAE and MAMCOMP-2003 and 2007 at Tehran in collaboration with ROPME and Iranian National Center for Oceanography. The IOC was responsible for planning and conducting all aspects of the MAMCOMP training programmes.

The IOC sponsorship of MAMCOMP was essentially based on the concept of national and regional "capacity building" of scientifically trained marine science professionals. The participants for the training programme are usually selected by a Programme Committee comprising senior scientists/ administrators from various institutions dealing with marine issues. About 20-30 participants were selected per year from the marine pollution control agencies and boards, R&D organizations dealing with marine science and environmental engineering, and academic institutions interested in marine science studies. While most of the participants were from the host country, on occasions, a limited number of participants from the IOCINDIO region countries and international participants were sponsored by the IOC. Although the training programme was originally intended to provide broad-based theoretical and experimental aspects of coastal marine science for working scientists, it has also served well as an introductory graduate course for students pursuing advanced university degrees at the Masters and Doctoral levels. MAMCOMP training programme is now reasonably known in marine science laboratories, academic institutions, marine environmental centres such as coastal pollution boards, and it has generated considerable interest in the IOCINDIO region in Integrated Coastal Area Management.

Julian Barbiere
ICAM Coordinator
UNESCO-IOC

Preface

This book deals with a collection of overview articles on two aspects of coastal oceanography: monitoring and modelling of coastal marine processes. Although numerous books have been written on both monitoring and modelling of coastal oceans, there is a practical need for an introductory multi-disciplinary volume to non-specialists in the field. The text is intended for graduate students and professionals who do not have extensive training in marine sciences and coastal zone management. This book will also support instruction of modelling and monitoring of coastal marine processes for short courses to mid-level scientists. As such, the articles in this monograph can be a valuable reference for practicing professionals.

The articles in the book, organized into four major themes, are written by experts in their disciplines. The first section introduces the complex physical processes with main emphasis on waste disposal in the coastal ocean. The articles in this section provide an overview of transport and diffusion processes in the marine environment. The review of fundamentals at this stage provides a common foundation of mathematical and field observational knowledge upon which the rest of the course is developed. Following this, examples of instrumentation techniques that are commonly used for measuring different properties of oceans are described with several examples of both in-situ and remotely sensed instrumentation. Coastal and estuarine transport and dispersion modelling is introduced in the next section with examples from different parts of the world. The last section provides an overview of coastal disasters such as tropical cyclones, storm surges and oil spills. Finally, we provide some overview articles on integrated coastal management with some regional examples and the application of GIS techniques for coastal zone management.

C.R. Murthy, Y.R. Rao
Environment Canada
National Water Research Institute
Burlington, Canada

P.C. Sinha
Indian Institute of Technology
New Delhi, India

Contents

Coastal Marine Environment: Theory and Measurements

Modelling of Coastal Marine Pollution

Coastal Marine Hazards

Coastal Marine Policy/Management

Coastal Marine Environment: Theory & Measurements

The Coastal Ocean

Y.R. Rao, C.R. Murthy and P.C. Sinha[1]

Environment Canada, Water Science & Technology
National Water Research Institute, 867 Lakeshore Road
Burlington, Ontario, Canada, L7R 4A6
[1]Centre for Atmospheric Sciences
IIT Delhi, Hauzkhas, New Delhi - 110016

INTRODUCTION

The coastal ocean extends from shorelines, beaches and estuaries across continental shelves and slopes to where exchanges and interactions occur with the deep ocean. Although the inshore boundary is normally the coastline, it may extend in some cases such as estuaries as far upstream as riverine cross-section where unidirectional downstream flows always occur irrespective of tidal flow conditions. The general offshore boundary is the continental shelf-break and the inshore boundary may extend as far as the river plains. Functionally it is the broad interface between land and water where production, consumption and exchange processes occur at high rates of intensity. Ecologically it is an area of dynamic biological activity, but with limited capacity for supporting various forms of human interactions.

The coastal ocean—where land, air and sea meet—is a region of very high physical energy and biological diversity that is heavily exploited by man. The coastal zone occupies only about 8% of the earth's surface but approximately 26% of the total global primary production occurs in this area and as much as 85-90% of the present world fisheries production is derived from the Exclusive Economic Zone (EEZ). Much of the world's arable lands and industrial development lie on the coastal plains and in lower river valleys. As a consequence, about 60% of the present world's population lives within 60 kilometres of the shoreline. It is estimated that in a few decades 75% of the world population will live within 60 kilometres of the coast. Over two thirds of the world's cities with populations greater than 1.6 million inhabitants are located in coastal areas, often in the vicinity of highly productive estuaries or coastal wetlands. In Southeast Asia, 65% of all major cities are on the coast. Population growth and population density are highest near the coastal zone and in many countries the coastal population growth rate is twice the growth rate inland due to heavy migration to coastal locations and cities. Urban coastal ocean problems pose serious threats to marine water quality and resources.

Therefore, the coastal ocean regions are the areas of most immediate interest to the public and most direct human impact occurs there. The coastal ocean and the adjoining terrestrial areas interact intimately. The coastal ecological systems are already stressed and degraded and the driving forces in these environments are no doubt anthropogenic. Through deliberate dumping and inadvertent action, coastal oceans have become the depositories of human and industrial wastes. Also, the rivers serve as natural conduits in transporting materials to the coastal ocean. The present quantity of domestic municipal and industrial wastes discharged into the coastal waters, estuaries and the open ocean precludes the possibility of economic alternative methods of waste disposal. All waste water used in man's activities ultimately finds its way to the aquatic and oceanic environments.

The coastal ocean is the focal point of inter-related water resources systems and should receive much greater attention in water resources research, planning and management. It is the coastline where the river meets the sea, where fresh groundwater is subject to salt-water intrusion, where the majority of urban centres' industrial complexes are located. Sustainable development of the coastal ocean must be based on interdisciplinary studies including socio-economic and political aspects. Coastal oceans are very important in several ways, not mutually compatible if carried to extremes and each with differing policy and management objectives. Neither total exploitation, nor complete conservation is an acceptable goal and hence a balance must be maintained. Ecological rehabilitation must now be an integral part of any new coastal ocean development programme. Integrated environmental and socio-economic studies must be initiated with a broad view of formulating coastal ocean management policies and strategies.

Chapter 17 of UNCED's Agenda 21 specifically calls for innovative approaches to "Integrated Management and Sustainable Development of Coastal and Marine Areas, including Exclusive Economic Zones, EEZ". It also calls upon countries to "co-operate in the development of co-ordinated, systematic observations, research, and management of coastal systems". In view of world-wide interest in coastal ocean issues, several international agencies have proposed activities to tackle coastal zone management.

COASTAL MARINE PROCESSES

The coastal zone is truly a dynamic ecological system with continuous natural erosion and accretion at the shoreline. At the coastal interface, the sea is shallow and the land is low. Sand and mud flats receive daily tidal floods and river run-off, while wind and waves bring continual change to the shoreline. However, it is man's activities which cause the greatest and most rapid change, and which are the primary reason for the concern with coastal resources management. The coastal ocean is particularly vulnerable to global changes such as climate change, sea level change, which is in itself a derivative of the climate change, and changes in uses of land and fresh water. These global changes may fundamentally modify geomorphologic, hydrodynamic, geochemical and biological processes in the coastal ocean and affect significantly transport of materials from the land to rivers and seas.

The physical transport processes are dominant in mediating geochemical and biological processes in the coastal ocean environment. Thus, it is very important to have a thorough understanding of the coastal physical processes responsible for the distribution and redistribution of chemical and biological species in the coastal ocean. The transport and fate of nutrients and contaminants discharged into the coastal zone is just one example. Their residence time and their degree of accumulation in the sediments (suspended as well as bottom) are partly by the physical exchange processes and partly by biotic processes active in the coastal regions. The coastal regions are not, however, isolated but are coupled to a greater or lesser degree by exchanges across the shelf-break involving transport of materials, momentum and energy.

Several physical factors combine to make the coastal ocean complex and unique in its hydrodynamics, and the associated physical transport and dispersal processes of the coastal flow field are equally quite complex to deal with. The first characteristic feature of the coastal ocean is its shallow depth, typically less than 200 m, compared with depths of 4000 m in the deep ocean. The edge of the continental shelf is usually marked by an abrupt increase in the bottom slope from an average of 1 in 500 to about 1 in 20. Because of the presence of bottom at a relatively shallow depth, currents near the bottom are often much larger than deep ocean. The bottom friction, which is negligible in the deep ocean, plays a significant role in their dynamics.

The presence of shoreline acts as a lateral constraint on water movements, tending to divert currents so that they flow nearly parallel to the shoreline. The shoreline also causes surface slopes to develop, which in turn react on and modify the water movements. The influx of freshwater run-off from the land, often after passing through the estuaries, has the effect of reducing the salinity, and hence also density of the coastal water. For a similar heat flux through the sea surface, the shallower water near the coast undergoes larger changes in temperature than deeper water. Because of these effects, coastal water exhibits large horizontal gradients of density, often associated with changes in currents.

Tide and Tidal Currents

The tides, which produce the rise and fall of water in the coastal zones, are generated in the deep oceans. But due to the above characteristics of coastal waters, the tides and tidal currents are considerably modified in the coastal zone compared to deep-ocean. Their magnitude is usually increased, sometimes by a large factor when resonance occurs between a tidal period and the natural period of oscillation of a coastal body of water.

Wind-driven Motions

Wind-driven currents are strongly affected by the presence of the coastline and the bottom. In some areas this gives rise to storm surges, while in others new effects are produced, such as occurrences of upwelling and downwelling or the generation of coastal jets.

Surface Waves: Surface waves are an important feature of oceans that get modified in the coastal waters. As waves travel into shallower water, the proximity of the bottom induces considerable changes in them and eventually causes them to break, dissipating most of their energy on the shore. The release of energy from the waves leads to the movement of large amounts of beach material in some areas and exerts considerable forces on natural and man-made structures.

Seiches: Standing waves cause much greater water displacements than surface waves and are, therefore, much more important in physical oceanography and limnology. Standing waves are a phenomenon occurring in all inland water bodies, but only in large basins we observe periodic rise and fall of the water surface. They are generally known as 'seiches'. The seiches are free surface waves, governed by similar dynamics as short, wind generated waves. The principal ingredients in the wave dynamics are acceleration of the water particles and pressure gradients generated by displacement of the free surface and the force of gravity.

Storm surges: A sudden strong wind will produce not only oscillating seiches, but also cause the water surface to set up or tilt, more or less in opposition to the wind stress, and for the duration of the wind. These changes in water level observed in response to extremely vigorous wind forcing are known as storm surges. The largest change in water level is produced by the sum of storm surge and tide. Storm surges are largest at the ends of an elongated basin, particularly when the long axis of the basin is aligned with the wind. In low-lying shores such events may cause flooding and increased erosion, with property damages and risk to human lives.

Topographic gyres: The wind drag is transferred from the surface downward by turbulent friction. In the closed basins, the transport of water through any cross-section averaged over the period of fundamental seiche is zero. Surface wind-driven flow must be balanced by a subsurface flow that is driven by pressure gradients. Close to the shore, wind drag is experienced all the way to the bottom, and this water is accelerated in the direction of the alongshore component of the wind. The balancing return transport occurs in the middle of the basin. Thus the forced, vertically averaged circulation takes the form of double gyre. The complicated vertical shear maintained during the active wind-forcing soon dies out, leaving this two-gyre motion behind. Within such cross-shore flows, the earth's rotational force and pressure gradients do not balance and a wave-like motion sets up. The two-gyre motion rotates counter-clockwise around the basin in the Northern Hemisphere. These motions are called topographic or vorticity waves. Unlike the influence of topography, the curl of the wind stress generates a single basin-wide gyre that can rotate around the basin, depending on the wind stress.

Coastal Jet: During strongly stratified regions the force of gravity suppresses turbulence. The vertical transfer of wind-imparted momentum is thus inhibited so much so that the shear stress in the horizontal planes within the thermocline is usually small. This is not true all of the time or everywhere; however, it has been observed in the coastal regions that at least at some distances from the shore the momentum of the wind induced coastal current is concentrated in the top, warm portion of the water column above the thermocline. This concentration of momentum in relatively shallow layer resulted in increased velocities, compared to their depth-averaged values. The region where such concentration was pronounced occupied a band of 5 km width. Their high velocity, shallow depth, and narrow width make it appear to describe the flow structure as 'coastal jets'.

Upwelling and downwelling: When wind blows over the stratified coastal waters, the initial transport is confined to the upper layer, which slides over the unperturbed lower layer. At the shores, accumulations of warm water force the thermocline down (downwelling), and where the warm water moved offshore, the thermocline must rise (upwelling). The strong tendency for the Coriolis force to steer flows in such a way that the pressure gradients are balanced by the Coriolis force limits the upwelling and downwelling zones to a narrow band along the shore line typically within the Rossby radius of deformation. The Rossby radius of deformation can be defined as the ratio between the typical velocity scale of surface or internal waves, and the Coriolis frequency.

Internal Kelvin waves: When the wind stops, the initial unbalanced state described above relaxes through the mechanism of internal Kelvin waves. Kelvin waves propagate along shore in a counter-clockwise direction in the Northern Hemisphere. Internal Kelvin waves are confined to a few kilometres from the shore, and with no motion in the perpendicular direction to the coast. The near-surface currents that moved in the downwind direction during the active wind phase now reverses during the propagation of these waves.

Near-Inertial motions: In large lakes and oceans the earth's rotation is often important and may influence the water motion. When the natural period of the oscillation is comparable to or greater than the inertial period (12/sin φ), the motions are affected by the earth's rotation. The inertial period is dependent on the latitude (φ) of the lake. During the stratified season away from the near-coastal regions, currents exhibit clockwise rotary motions close to the inertial period. The main features may be explained in terms of balance between the Coriolis force and the centrifugal force. A sudden wind impulse lasting less than half the inertial period is favourable to the creation of inertial motions. Observations also showed similar motions in the deeper layers where the direction is generally opposite to that of surface oscillations. These motions are called Poincare waves, which are similar to internal seiches in lakes and inland seas. The currents are accompanied by vertical oscillations of thermocline at the wave period. These waves are hybrid between pure inertial motion described above and gravity waves; the current vector rotates in clockwise direction at a frequency close to but usually larger than local inertial frequency.

Vertical convection currents: Apart from wind- or river-induced circulation, currents can also be generated internally due to stratification effects. These currents draw their energy from changes in density due to surface cooling and heating. Differential cooling and heating is also very important in shallow zones and may be responsible for flushing of littoral waters.

There are several conceptual models and theoretical ideas concerning the hydrodynamics and transport and dispersion in the coastal ocean. However, it is difficult to identify the relative effects of different physical processes in any specific situation to arrive at a predictive deterministic model. Recognising this difficulty, it is therefore not surprising that coastal marine research places considerable emphasis on carefully designed large scale field experiments at several coastal sites with a view to formulate a climatology of the coastal physical environment in terms of the dominant circulation features and transport and dispersion processes. The results and data obtained from the experiments facilitate in parameterising the coastal marine physical processes necessary for developing predictive coastal transport models. Generally there are several interrelated objectives for such coastal marine experimental programmes. Some objectives are site-specific in nature (for example siting Sewage Outfalls in the coastal ocean) and others are towards the understanding of fundamental coastal marine processes.

WASTE DISPOSAL

Waste disposal into the ocean has come a long way from the time when there was unplanned and indiscriminate dumping of wastes. The alarming marine pollution that resulted from such practice has, in most places, been minimised in recent years in many countries. Now, waste disposal into the coastal ocean is a carefully controlled operation based on extensive scientific and engineering research and design. However, indiscriminate dumping still occurs in many countries even today.

In the early stages of waste disposal into the coastal ocean, it was the usual practice to discharge effluents from the end of a pipe or submarine outfall in a single large stream. The buoyancy of such a flow was so strong in relation to its mixing rate that the effluent plume would invariably rise to the surface and spread as a surface current. Pollution of the shoreline was likely when onshore currents occurred. Two significant advances in techniques of waste disposal into the coastal ocean have minimised this possibility of shoreline and beach pollution:

(i) Introduction of multi-port diffusers: Very large multiple jet diffusers have been successfully designed and operated without clogging and maldistribution of flow. Diffusers greatly enhance initial dilution of waste effluent with receiving waters and dilution ratios of 200:1 or even 300:1 are commonly achieved with well designed diffuser systems within a very short distance from the point of discharge.

(ii) Concept of submergence: The natural density stratification of the ocean has been used to a great benefit in keeping waste discharges submerged in the lower layers of the ocean. A remarkable change in the flow pattern occurs when there is a slight density gradient in the receiving waters, caused by temperature and salinity changes with depth. In the ocean, the stratification is almost always hydrodynamically stable, with warmer (or less saline) layers at the top. The buoyant plume may no longer rise to the surface because the plume loses its buoyancy before it gets there. Initial dilution of the plume due to multiport diffuser is responsible for the loss of buoyancy of the plume. In actuality, however, the density of the entrained fluid decreases as the plume rises; nonetheless, a point of neutral buoyancy will be reached at some depth. Theoretical prediction of the maximum height of rise of a plume in a stratified environment is possible and of special interest in the coastal ocean, where submergence of the cloud of mixed sewage and sea water is beneficial in controlling marine pollution. The maximum height of rise may be made less than the total depth by making the discharge per port sufficiently small in relation to the density gradient. To produce a submerged sewage cloud one must first measure the natural density stratification in the ocean and then design a diffuser system to produce small enough jets so that the stratification may act as a brake on the buoyant rise of the wastewater plume. Essentially three stages of mixing and dilution of the wastewater field are encountered: (i) Initial jet or plume mixing: initial dilution; (ii) Development of a homogenous waste field following initial jet mixing: transition zone; and (iii) Dispersion of the waste field due to natural oceanic turbulence and current shear: far-field dilution.

Planning new coastal waste disposal systems in the coastal ocean should consider the following: (i) Water quality standards to be met in the receiving waters; (ii) Degree of treatment: primary treatment: screening, sedimentation from removal of settleable and floatable solids, and chlorinating as required to control bacteria and viruses; secondary treatment to achieve the necessary biodegradation which is often expensive. Properly designed marine outfall systems can provide the secondary treatment, for example, organic wastes are digested by the natural ocean life; (iii) Detailed oceanographic surveys: salinity, temperature and density stratification; coastal flow and dispersion climatology: current speeds, directions, persistency of currents, coastal dispersion coefficients etc.; submarine topography and geology and the characteristics of marine biology, turbidity, DO levels; and (iv) Dilution predictions using well established outfall diffusion models.

In the actual design of a waste disposal system, which is unique for each site, the engineer can choose the location, depth, and the length of the diffuser and the number and size of its discharge ports. Receiving water quality objectives have the major effect on the design. Design decisions can be made only in a systems context, taking into account the degree of treatment, outfall and diffuser hydraulics, the various stages of dilution, the decay rate of bacteria and other substances, and the density stratification, prediction of submergence and the current regimes in the receiving water body. In some instances a submerged waste field may be desirable, while in areas such as estuaries and large lakes it may not be desirable.

Ocean outfalls will not become obsolete even when much of the waste water is reclaimed for reuse. With growing demands for waste water, there will undoubtedly be extensive reclamation, because such water is much cheaper. But there will always be substantial outflows to the ocean because only part of the waste water can be reclaimed and reused and many types of industrial wastes are unsuitable for reclamation. Further, waste products from waste water reclamation plants must go somewhere, and the ocean is the most suitable place.

Deepwater ocean outfalls have virtually eliminated many coastal marine pollution problems. In some cases, one would have difficulty in finding any evidence at all of waste outfall disposal. Although, waste field is submerged most of the time and therefore out of sight, there are subtle ecological changes taking place in the ocean environment. These ecological changes should be identified and evaluated through biochemical and water quality monitoring and research; we cannot eliminate all ecological changes. However, by applying fluid mechanics, oceanography, and careful engineering research and design, we can obtain high dilution through dispersion and thus minimise the long range ecological effects. In heavily industrialised and urban coastal areas of India, the direct disposal of industrial and municipal effluents into the coastal ocean and the indiscriminate use of urban waterways, canals, streams and rivers as carriers of the waste effluents pose a threat to marine water quality and thus depriving alternate uses of coastal areas for recreation, tourism, and fisheries development and management. In some situations coastal marine environments have been stressed beyond their natural assimilative capacity to absorb the waste effluents with noticeable detrimental effects on the water quality and aesthetic value. The scientific and engineering aspects of the design, construction, maintenance and operation of marine outfall systems in India are very much in their infant stage at the present time. Therefore, the majority of the recently laid marine outfalls have been plagued with frequent malfunction and in some cases total failure.

Introduction to Transport Phenomena

G. Jayaraman

Centre for Atmospheric Sciences
IIT Delhi, Hauzkhas, New Delhi- 110016

INTRODUCTION

The study of transport phenomena—i.e., transfer of mass, momentum and energy—is increasingly recognized as a unified description of fundamental importance. It is a topical extension of the concepts and laws of mechanics, thermodynamics and fluid mechanics. The prediction of the mechanical transport of substances in the ocean is a difficult task since it requires knowledge of many other interrelated factors. These factors include convection (transport by the moving waters of the ocean), physical (transition between different states, nuclear decay), chemical (chemical decay of substances, reaction with other substances) and biological (accumulation and transport of substances by living organisms). The transport is not only by the mean current velocities but also by the presence of random chaotic fluctuations in the velocity field. For calculating advective transport of substances, data on the vector field of mean current velocities for the ocean region are needed as well as their variations with time.

The transfer process typified by a diffusion process may be defined as the tendency towards equilibrium—a process which tends to establish equilibrium. For example, when a small amount of perfume vapour is sprayed into a room, the mass transfer process causes the perfume vapour to diffuse throughout the room until its concentration is uniform—an equilibrium condition. In all transfer processes, we are chiefly concerned with rates at which changes in properties of a system occur. In the flow of a viscous fluid, the frictional phenomenon or viscous stresses may be related to the rate of change of momentum of a system. Likewise, mass diffusion in any one of the various forms may be related to the rate of change of composition of a mixture due to transfer of one of the component species.

Microscopic theories of transfer processes are based on the phenomenological approach in which the basic transfer relations are postulated from experience without reference to the details of mechanisms of transfer.

By definition, a transfer process consists of net flow of a property under the influence of a driving force. The rate of transfer is the flux and the intensity of the driving force is the potential gradient. The transfer process (or flux) takes place in the direction of decreasing potential.

We give below the phenomenological rate equations for transfer of *momentum* and *mass*.

(a) Newton's Equation of Viscocity

Consider the motion of a fluid between two very long parallel plates, one of which is at rest and the other moving with a constant velocity parallel to itself. Let the distance between the plates be h, the pressure being constant throughout the fields. Since the fluid adheres to both the walls, its velocity at the lower plate is zero and that at the upper plate is equal to the velocity of the plate, U. Moreover, the velocity distribution in the fluid between the plates is linear, so that the fluid velocity is proportional to the distance y from the lower plate. Thus we have,

$$u(y) = \frac{y}{h}U \tag{1a}$$

$$\left(\tau + \frac{\partial \tau}{\partial y}dy\right)dx - \tau dx = \frac{\partial \tau}{\partial y}dx\,dy \tag{1b}$$

In order to support the motion, it is necessary to apply a tangential force to the upper plate, the force being in equilibrium with the frictional forces in the fluid. It is known from experiments that this force per unit area of the plate is proportional to the velocity U of the upper plate and inversely proportional to the distance h. The frictional force per unit area denoted by τ (frictional shearing stress) is, therefore, proportional to U/h, for which, in general, we may also substitute $\frac{du}{dy}$. The proportionality factor between τ and $\frac{du}{dy}$ which we shall denote by μ, depends on the nature of the fluid. It is small for "thin" fluids, such as water or alcohol, but large in the case of very viscous liquids such as oil or glycerin. Thus, we have obtained the fundamental relation for fluid friction in the form

$$\tau = \mu \frac{du}{dy} \tag{2}$$

The quantity μ is a property of the fluid and depends to a great extent on its temperature. It is a measure of the *viscocity* of the fluid. The law of friction given by equation (2) is known as *Newton's law of friction.* Equation (2) can be regarded as the definition of viscocity.

The dimensions of μ from (2) are

$$\frac{FT}{L^2} \text{ or } \frac{M}{LT} \tag{3}$$

where symbols F, T, L and M represent the primary dimensions of force, time, length and mass respectively. Thus in CGS units, μ may be expressed in gm/cm.sec.

It has been found useful to define another quantity known as kinematic viscosity and denoted by v:

$$v = \frac{\mu}{\rho} \tag{4}$$

where ρ is the fluid density. It is readily seen that v has the dimensions of L^2/T or cm^2/sec.

We shall confine our attention to Newtonian fluids, which includes all gases and most liquids. It should be understood, however, that many industrially important fluids, such as molten plastics are non-Newtonian.

(b) Ficks' Equation of Diffusion

Consider two parallel plates with initially dry air between them, the bottom plate being covered with gauge and the top plate coated with a substance such as silica gel which absorbs essentially all water vapour which it contacts. Suddenly the gauge is wetted with water so that the partial density of the water vapour at the wet surface is maintained at C gms water vapour per cm^3. Then diffusion takes place until a steady state is reached. At the silica gel surface, c is assumed to be zero

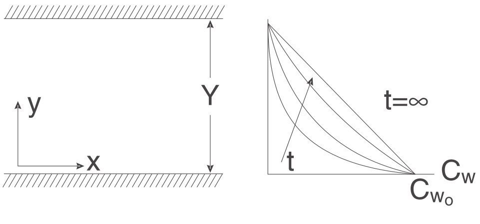

Fig. 1: Concentration distribution in a viscous fluid between two parallel plates.

Experimental evidence indicates a direct proportionality between the diffusion rate of water vapour and the concentration gradient. In the steady state or in general, at any position during the transient, the flux J is given by

$$J = -D\frac{\partial c}{\partial y} \tag{5}$$

where D is called the diffusivity or coefficient of diffusion and has the units L^2/T such as cm^2/sec. Equation (5) is called the Ficks' equation.

The equations (2) and (5) are not in fact laws of nature, but rather definitions of μ and D, which are found experimentally to be properties of the material.

(c) Diffusivities

Among the transfer coefficients defined by the rate equations, we note that the kinematic viscosity v and the diffusion coefficient D have the same dimension L^2/T. Clearly, a dimensionless number can be formed from the ratio of any two of these quantities. Thus, the

$$\text{Schmidt number } Sc = \frac{\nu}{D} = \frac{\mu}{\rho D} \tag{6}$$

It is a significant parameter of isothermal systems undergoing simultaneous momentum and mass transfer processes. It is approximately unity in gases, but is large for liquids.

CONSERVATION LAWS FOR ONE-DIMENSIONAL CASES

In transfer processes, we are chiefly concerned with finding out the rates at which some property of a system changes. In most instances, we are interested in changes due to fluxes of that property crossing a control surface, and in some special cases we are able to postulate from experience that the property is conserved. We shall formulate a mathematical statement of the conservation laws for certain one-dimensional cases.

Consider the two systems discussed in the previous section. For a fluid particle whose direction of motion coincides with x direction, it is found that the resulting shearing force is equal to

$$\left(\tau + \frac{\partial \tau}{\partial y} dy\right) dx - \tau \; dx = \frac{\partial \tau}{\partial y} dx \; dy \tag{7}$$

Hence the frictional force per unit volume is equal to $\frac{\partial \tau}{\partial y}$, or from (2)

$$\frac{\partial \tau}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) \tag{8}$$

By the principle of conservation of momentum, this should equal the rate of increase of momentum of the fluid in the element, or $\frac{\partial}{\partial t}(\rho \Delta x \; \Delta y \; \Delta z \, u)$ or $\frac{\partial}{\partial t}(\rho u)$ per unit volume.

Equating these for constant ρ, we get

$$\rho \frac{\partial u}{\partial t} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) \tag{9}$$

The conservation equation for mass transfer follows a similar development. If the space between $y = 0$ and $y = h$ is air with water vapour in dilute concentration diffusing from one wall to the other, the net rate of mass of water vapour diffusing into the element $\Delta x \, \Delta y \, \Delta z$ is $\frac{\partial}{\partial y}$ $(D \, \Delta x \, \Delta y \, \Delta z)$. Then, by conservation of mass this should equal the rate of accumulation of water vapour in the element, $\frac{\partial}{\partial t}$ $(c \, \Delta x \, \Delta y \, \Delta z)$. Equating the two we get,

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y}(D\frac{\partial c}{\partial y}) \tag{10}$$

Equations (9) and (10) have a striking similarity. This comparison shows the desirability of interpreting τ as a *flux of momentum*. This similarity of mathematical form plus similarity of boundary conditions defines a group of processes which are said to be analogous. It must be emphasized that this one-to-one correspondence, although valid for certain of the simple cases, cannot be extended to all cases. The conservation equations and rate equations applicable to the general processes in three-dimensional and including external force fields, chemical reactions, coupling phenomena etc. are not analogous in form.

CONTINUITY EQUATIONS

Relations expressing the overall continuity of matter in flowing systems will be useful in simplifying conservation equations for transfer processes in non-stationary systems. Consider a flow of a single-phase single-component fluid with velocity $\bar{v}$ having u, v and w components. The x direction flow rates entering and leaving a control volume $\Delta x \, \Delta y \, \Delta z$ fixed in space are shown in Fig. 2.

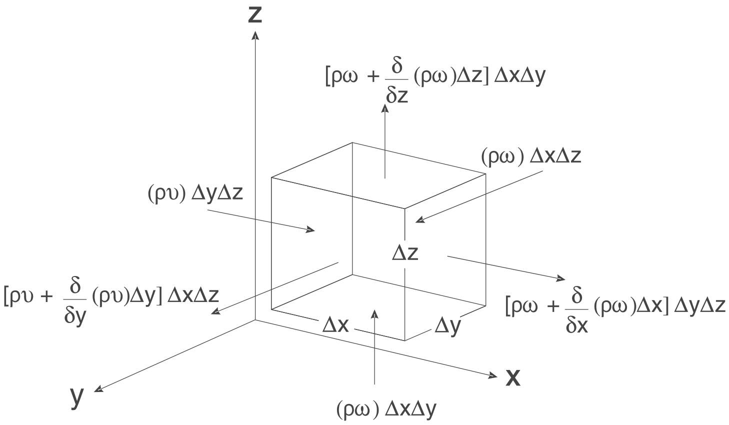

Fig. 2: Volume element for deriving continuity equation.

The net fluxes of mass in three component directions are then:

$$\left.\begin{aligned} x\ \text{direction}: &\frac{\partial}{\partial x}(\rho u)\,\Delta x\ \Delta y\ \Delta z \\ y\ \text{direction}: &\frac{\partial}{\partial y}(\rho V)\,\Delta x\ \Delta y\ \Delta z \\ z\ \text{direction}: &\frac{\partial}{\partial z}(\rho w)\,\Delta x\ \Delta y\ \Delta z \end{aligned}\right] \tag{11}$$

The sum of these will equal the rate of change (decrease) of mass within the control volume, $-\left(\frac{\partial \rho}{\partial t}\right)\Delta x\ \Delta y\ \Delta z$, or dividing by $\Delta x\ \Delta y\ \Delta z$,

$$-\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho V) + \frac{\partial}{\partial z}(\rho w) \tag{12}$$

or

$$\frac{\partial \rho}{\partial t} + (\nabla . \rho \bar{V}) = 0 \tag{13}$$

This is known as the continuity equation or equation of conservation of mass. If the density is constant in time and space, equations (12) and (13) are reduced to

$$\frac{\partial u}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{14}$$

or

$$\nabla . \bar{\nabla} = 0 \tag{15}$$

EQUATION OF MASS DIFFUSION IN STATIONARY MEDIA

The mass balance for component diffusing through a control volume with sides in a solid may be obtained as follows, where J_x, J_y, J_z are the mass fluxes in the x, y, and z directions respectively.

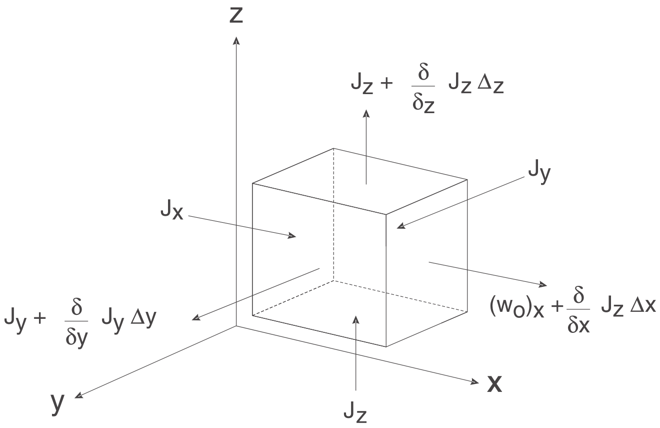

Fig. 3: Volume element for deriving mass diffusion equation.

Net transfer of C_a by diffusion in the x-direction

$$\frac{\partial}{\partial x}(J_x)\Delta x\ \Delta y\ \Delta z \tag{16}$$

Similar expressions may be written in the y and z directions. Rate of production or immobilization of C_a within the volume:

$Q_{a=}$ $\Delta x\ \Delta y\ \Delta z$ where Q_a is the rate of production per unit volume.

Rate of change of concentration of C_a within the volume

$$\frac{\partial C_a}{\partial t}\Delta x\ \Delta y\ \Delta z \tag{17}$$

The mass balance, dividing throughout by $\Delta x\ \Delta y\ \Delta z$, is given by

$$\begin{aligned}\frac{\partial C_a}{\partial t} &= -\frac{\partial J_x}{\partial x}-\frac{\partial J_y}{\partial y}-\frac{\partial J_z}{\partial z}+Q_a \\ &= -\frac{\partial}{\partial x}\left(D\frac{\partial C_a}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial C_a}{\partial y}\right)+\frac{\partial}{\partial z}\left(D\frac{\partial C_a}{\partial z}\right)+Q_a\end{aligned} \tag{18}$$

or

$$\frac{\partial C_a}{\partial t} = (D\nabla . C_a)+Q_a \tag{19}$$

If D were independent of x, y, z and C_a and Q_a were zero, then

$$+\frac{\partial C_a}{\partial t} = D\ \nabla^2 C_a \tag{20}$$

MOMENTUM TRANSFER IN LAMINAR FLOW

General momentum conservation equations–Navier Stokes Equations

In deriving equations (1)-(10), we presented a one-dimensional statement of the momentum conservation law, our purpose then being to emphasize the area of similarity among the conservation laws of various transferable properties. We considered only viscous shear forces (or equivalent momentum transfer), expressed by the simple one-dimensional rate equation. We now write a more general form of the momentum conservation equations in three dimensions.

In general, forces acting on a fluid system may be classified as body forces proportional to the volume or mass of the system such as gravity, and surface forces proportional to the area of surface on which they act, such as pressure and viscous forces.

The presence of viscous force in a fluid system gives rise to three-dimensional stress-strain relations analogous to the well known stress-strain relations (Hooke's law) for an elastic solid. However, whereas in an elastic solid stresses are proportional to strain, in fluids stresses are empirically found to be proportional to the rate of strain, expressible in terms of velocity gradients. Physically, this means a fluid offers no resistance to change of shape but resists time rate of change of shape. The general three-dimensional stress-strain relations for a viscous fluid are given below. We shall accept them as empirical formulations, although precise expressions for gases can be derived from the kinetic theory.

Fig. 4: Volume element with arrows indicating the positive direction of *x*-direction stresses.

Figure 4 shows the assumed positive direction of *x*-direction shear stresses. Similar sets exist in other two directions.

$$\left.\begin{aligned}
\sigma_x &= -p + 2\mu\frac{\partial u}{\partial x} - \frac{2}{3}\mu\nabla.\bar{V} \\
\sigma_y &= -p + 2\mu\frac{\partial v}{\partial y} - \frac{2}{3}\mu\nabla.\bar{V} \\
\sigma_z &= -p + 2\mu\frac{\partial w}{\partial z} - \frac{2}{3}\mu\nabla.\bar{V} \\
\tau_{xy} &= \mu\left(\frac{\partial u}{\partial y} + \frac{\partial V}{\partial x}\right) = \tau_{yx} \\
\tau_{yz} &= \mu\left(\frac{\partial V}{\partial z} + \frac{\partial w}{\partial y}\right) = \tau_{zy} \\
\tau_{xz} &= \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) = \tau_{zx}
\end{aligned}\right] \qquad (21)$$

In these equations, μ is a constant of proportionality called, as before, coefficients of viscosity; its definition is more general than that given by equation (1). σ's are normal stresses, composed of nontrivial normal stresses