Chapter 1

INTRODUCTION

Human beings live in all parts of the world from antarctica to the deserts. Humans can live and work comfortably round the year only in a very few favoured areas of earth's temperature zone. In other places, the environmental conditions vary from inhospitable to hazardous. Although, humans are equipped with unique features like acclimatization and defence mechanisms against heat and cold for survival, these are not sufficient to provide comfort in inhospitable environment. Therefore, from earliest times man has striven to change the indoor thermal environment. The science and practice of creating a controlled climate in indoor spaces is called air-conditioning. In the beginning, the purpose of air-conditioning was to provide comfort which was later extended to industrial air-conditioning for increased productivity and abatement of pollution and to specialized areas of modern progress requiring clean rooms. Hence modern air-conditioning is classified into comfort air-conditioning, industrial air-conditioning and clean rooms.

Considering that upto 90% of a typical person's time is spent indoors, the expectation of the occupants for thermally comfortable indoor climate has risen. Thermal comfort according to ISO 7730 is " That condition of mind which expresses satisfaction with the thermal environment". This is closely related to metabolic heat production, its transfer to the environment and the resulting physiological adjustments and body temperatures. The heat transfer depends upon air speed, mean radiant temperature, relative humidity, turbulence level, clothing *etc.*. In addition to thermal comfort, indoor air quality has become a topic of concern. The parameters of thermal comfort and indoor air quality (IAQ) are interrelated and have profound effect on indoor climate. A proper evaluation of indoor climate requires precise knowledge of the distribution of air velocity, temperature and species throughout the room. It was recognised by W. H. Carrier[2], one of the founders of air-conditioning systems with the statement "No air-conditioning is better than its air distribution".

ASHRAE[3] defines acceptable IAQ as " Air in which there are no known conminants at harmful concentrations as determined by cognizant authorities and with ıich a substantial majority (80% or more) of the people exposed do not express distisfaction".

The importance of proper IAQ (Linder *et al.*[4]) has come to light in recent ars. Poor IAQ has been linked to numerous adverse mental and physical health 'ects that decrease worker productivity and can lead to sick buildings. Over the st several decades, our exposure to indoor air pollutants has increased due to a riety of factors including:

(i) the construction of more tightly sealed buildings;
(ii) reduced ventilation rates to save energy and running cost;
(iii) use of synthetic building materials and furnishings;
(iv) the use of personal care products;
(v) pesticides and house keeping supplies.

In addition, human activities and decisions, such as deferring maintenance to save ›ney can lead to problem.

The indoor environment in any building is a result of the interactions among the e, climate, building structure and mechanical systems, construction techniques, ntaminant sources (outside, inside and part of the building) and building occunts. The effects of IAQ problem are often non-specific symptoms rather than ›arly defined illness. Symptoms (which can occur singly or in groups) commonly tributed to IAQ problems include:

(i) headache, fatigue and shortness of breath;
(ii) sinus congestion, coughing and sneezing;
(iii) eye, nose, throat and skin irritation;
(iv) dizziness and nausea.

These symptoms, however, may be caused by other factors also and are not nec›sarily due to air pollutants.

1 *Basic Air-conditioning problem*

An understanding of the interaction between the building, its usage and the air-conditioning system is essential if good design is to be achieved. The quality of the environment produced by air-conditioning is also important and depends to a large extent on what happens in individual spaces. The creation of acceptable conditions by the manipulation of conditioned air within a space is called here the basic air-conditioning problem and is the principal subject of the thesis.

Excessive thermal heat gains and adverse contaminant levels result from conditions and decisions not normally within the control of the air-conditioning engineer, yet these may affect markedly the extent to which a uniform thermal environment can be provided. When close control over conditions becomes of prime importance, limitations may have to be imposed on the design of the enclosure and perhaps also on the nature of the occupancy. This is a common occurrence in the design of research laboratories, e.g. where windows have to be omitted to achieve close temperature and humidity control.

The air-conditioning consists of making adjustments to balance the heating or cooling loads by the air-conditioning equipment for the space as a whole so that conditions will be maintained everywhere in the occupied space within the acceptable limits.

A common way of arranging for removal of heating/cooling loads and contaminants is to draw a definite amount of air from the space and recirculate it after conditioning it by the air-conditioning equipment. The conditioning of the air, which may include filtering to remove dust and blending with a certain proportion of fresh air for ventilation, heating/cooling, dehumidifying/humidifying is often carried out outside the conditioned space.

In normal air-conditioning practice, great advantage is taken of the fact that of a whole space only the part that is to be occupied need be held within acceptable limits for occupancy. The part of the room volume above the occupied zone may be used to advantage as a distribution and mixing zone. This requires that the primary air be projected with sufficient velocity to entrain room air by induced secondary circulation in amounts up to 3-5 times its own volume before it enters the occupied zone, and at the same time provide the best possible distribution and movement of air throughout the occupied zone. This is not easy to accomplish and it constitutes one of the great challenges to the designer of the air-conditioning system. Clearly the extent to which uniform air temperature, air movement and relative humidity can be achieved throughout the occupied zone is greatly dependent on it.

Distributions of the air in a room is usually accomplished by one or more of the following three factors:

- Inertia of the primary stream;
- Buoyancy due to differences in temperature;
- displacement resulting from the general movement caused by the continuous over-all introduction and withdrawal of air.

A realistic analysis must take into account all the three factors in designing for adequate room air distribution. The supply registers must also be designed to assist in the scheme of air-distribution selected. The size, location, orientation, spacing and amount of air handled by the register are all important factors affecting the room air distribution.

If the "throw" of a register is too large, the primary air stream may directly enter the occupied zone or may "splash" on a wall and be deflected downward. Heated air streams rise when projected horizontally while the cooled streams fall due to buoyancy and must be given an appropriate initial deflection to achieve the desired distribution.

1.2 Control of Indoor Air Pollutants

There are many ways in which a practitioner can intervene to prevent or control the indoor air contamination problems. Control strategies are usually categorized as:

- Source control;
- Ventilation;
- Air-cleaning (by filter or air washer);
- Exposure control.

Successful mitigation of pollution often involve a combination of these strategies.

1.2.1 Source control

All efforts to prevent or correct IAQ problems should include an effort to identify and control the sources of pollution. Source control is generally the most cost effective approach to mitigate IAQ problems in which point sources of contaminants can be identified. In the case of a strong source, source control may be the only solution that will work. It can be done by removing or reducing the strength of sources, covering or sealing the source, cleaning and disinfecting the area which is contaminated for example by fungal or bacterial growth.

1.2.2 Ventilation

Ventilation modification is often used to correct or prevent indoor air quality problems. This approach can be effective either where the buildings are under-ventilated or where a specific contaminant source can not be identified. Ventilation can be used to control indoor air contaminants by

- Diluting contaminants in the indoor air
  - by increasing the total quantity of supply air (including outdoor fresh air);
  - by increasing the proportion of outdoor fresh air to total air;
  - by improving the air distribution.
- Isolating or removing contaminants by controlling air pressure relationship
  - by installing effective local exhaust at the location of the source;
  - by avoiding recirculation of air that contains contaminants;
  - by locating occupants near supply diffusers and sources near exhaust registers;
  - by using air-tightening techniques to maintain pressure differentials and eliminate pollution pathways;
  - by closing the door where it is necessary to separate zones.

Most ventilation deficiencies appear to be linked to inadequate quantities of outdoor air. However, inadequate distribution of ventilation air can also produce IAQ problems. Diffusers should be properly selected, located, installed and maintained so that supply air is evenly distributed and blends thoroughly with room air in the breathing zone. Short circuiting occurs when clean supply air is drawn into the return air plenum before it has mixed with the room air and therefore fails to dilute contaminants. Mixing problems can be aggravated by temperature stratification. Stratification can occur, for example in a space with high ceilings in which ceiling-mounted supply diffusers distribute heated air.

Increased ventilation may lead to some additional IAQ problems if proper care is not taken. The limitations and side effects of increased ventilation are as follows:

- mitigation by increasing the circulation of outdoor air requires good outdoor air quality;
- increased supply air at the problem location might mean starving the other areas of supply air;
- increased total air in the system and increased outdoor air will both tend to increase energy consumption and require increased equipment capacity;
- any approach which affects airflow in the building can change pressure difference between rooms (or zones) and between indoors and outdoors, and might lead to increased infiltration of unconditioned outdoor air/ leading to increased equipment capacity;
- increasing air in a VAV system may overcool an area to the extent that terminal reheat units may be needed.

1.2.3 Air-cleaning

Air cleaning is usually most effective when used in conjunction with either source control or ventilation. However, it may be the only approach when the source of pollution is outside the building. Most of the time, air cleaning in a large building is aimed primarily at preventing contaminant build-up in HVAC equipment and enhancing equipment efficiency. Air cleaning can be done by particulate filtration, electrostatic precipitation, negative ion generation, gas sorption *etc.* and are not the topic of investigation.

1.2.4 Exposure control

Exposure control is the administrative approach to mitigate indoor contaminants and uses behavioural methods by scheduling contaminant producing activities to avoid complaints and relocating susceptible individuals away from the contaminated area.

1.3 *Clean Rooms*

Dilution with outdoor air is a primary means of control of indoor air contaminants, and the energy associated with heating/cooling and humidifying/dehumidifying this outdoor air is a significant proportion of heating/cooling load. Now-a days study of airflow system plays a vital role for the construction of clean rooms/work stations which are mainly used for electronic and pharmaceutical industry. Normally clean rooms are of two types:

- Laminar air flow (LAF) clean rooms;
- Non-laminar airflow clean rooms.

1.3.1 Laminar airflow clean rooms

Laminar air flow(LAF) systems([5]) in the area of ventilation are very important for many critical applications in health care, science and industry. Manufacturers of pharmaceutical products rely on the performance of LAF clean work stations and cleanrooms to ensure that the product standards are achieved. LAF work station is an ultra-clean enclosure with a work-zone which protects a product from ambient contamination, but it does not provide protection to the personnel or to the environment. This is a self contained enclosure or cabinet incorporating fans and high-efficiency particulate air (HEPA) filters. The sterility of drug products and the health and safety of personnel involved in the preparation and dispensing of cytotoxic drugs depends on the effective operation of cytotoxic drug safety cabinets (CDSCs) and the special clean rooms in which their installation is recommended.

Clean rooms can be defined as rooms, or set of rooms in which the concentration of airborne particulate matter is maintained within established limits, and where other factors are controlled to within defined limits. These rooms are designed to provide control of various environmental factors including the following:

- Viable and non-viable airborne particles;
- Airflow patterns;
- Temperature and humidity;

- Containment of hazardous aerosols;
- Air pressure;
- Operating procedures.

These factor can be controlled with proper design of ventilation system.

1.3.2 Non-laminar airflow system

Non-laminar airflow rooms incorporate terminal HEPA-filtered air supply. These are pressure-controlled and provide means of controlling other environmental factors such as temperature and relative humidity.

1.3.3 Requirements for the clean rooms for aseptic production

- Cleanrooms should be constructed so that only HEPA-filtered air enters the room. HEPA filters should be installed at the "terminal point", i.e. at the point of air entry into the clean room. Filter-face velocity should be $< 0.6m/s$. Air supply to the clean room should be at a high level with air relief(exhaust) at a low level on the opposite end of the room. The air inlets should be located at the designated 'clean' end/side of the room. This arrangement will generate an airflow pattern which is essentially unidirectional, and will sweep contaminants from the 'clean' to the 'dirty' end.

- LAF cabinets should be installed at the 'clean' end of the room and should be located below a HEPA filter inlet. The inlet and LAF unit should be juxtaposed so that the area around and underneath the cabinet is flushed with HEPA filtered air. Cabinets should be located in a dust-free area away from the influence of air currents; sources such as air-conditioning inlets, doors and windows. Personnel traffic can generate air movements with velocity exceeding those produced by the cabinet, hence the cabinets should be kept away from these areas.

- Air supply to the clean room should be such as to achieve a room air-change rate of $> 20/hr$. Higher air change rates ($> 30/hr$) will enhance air cleanliness.

When the doors are kept open, the supply-air volume should maintain an outward flow of air to prevent the entry of contaminants through doors. Cleanroom air pressure should be higher (approximately $30Pa$ gauge) than that of the surrounding controlled area. The pressure difference between the zones should be $> 15Pa$.

- The Air lock pressure should be 15 Pa gauge. Suitable manometers should be installed outside the airlock to indicate the operating room pressures of the facility. Unless otherwise specified, the room temperature within the range of $16°C$ to $18°C$ and relative humidity of 50% to 60% are typically provided.

1.4 Ventilation systems

Generally, the modern buildings are made more leak tight than those built even 10 years ago. The tight construction of building ([6]) reduces unintended infiltration and exfiltration. This can result in an accumulation of odours, humidity problems and even building related illnesses due to poor indoor air quality (IAQ) referred to as Sick Building Syndrome. An active ventilation system which continuously exhausts stale air while bringing in fresh outdoor air avoids these problems. There are three general types of active ventilation systems in common use:

- Continuous exhaust (CE) type;
- Continuous supply (CS) type;
- Balanced ventilation systems.

CE ventilation systems are the least expensive type of active ventilation systems. CE systems often replace several existing bathroom fans with a single ducted central fan. These central systems can cost the same or slightly more than conventional bathroom exhaust fans. CE systems are quieter since there is only one fan located farther from a home's occupants. CE systems also have a longer equipment life since they employ more durable fans. However, caution needs to be exercised when using CE ventilation systems in conjunction with inefficient atmospheric vented heating appliances. Negative pressure created by the exhaust fan may cause back-draft of dangerous combustion gases into the home. To avoid this, a passive fresh air supply duct, vented (sealed combustion) furnaces/hot water heaters should be used.

CS ventilation systems are similar to CE systems except that these bring in the fresh air rather than exhausting it. This action pressurizes the house and forces air to leave through gaps in the home's structure or through openings specifically designed as outlets. While less common than other ventilation strategies, CS systems typically have low installation costs and help minimize back-drafting of combustion equipment. However, CS systems are not appropriate in cold climates where they can push warm indoor air into wall cavities causing condensation on cold outside surfaces. The resulting condensate can be significant.

Balanced ventilation systems offer all the benefits of CE and CS systems with a few disadvantages. With a balanced ventilation system, one can intentionally bring the fresh air in through a single inlet and expel it through a single outlet. This strategy provides a control in case the fresh air enters and the stale air leaves the house. With improved control, the ventilation system requires lower capacity to maintain comfort and freshness indoors. "Balanced ventilation systems have one primary disadvantage of higher installation cost. However, because both incoming and outgoing airflows are controlled, operating costs can actually be reduced by incorporating heat recovery in extreme climates. These savings are possible by an air-to-air heat exchanger in the ventilation unit that transfers heat from exhaust air to supply air or vice versa.

Balanced ventilation is accomplished by introducing 'clean' air into a space which is either mixed with the air already present in the enclosure to give 'mixing' or 'dilution' ventilation, or is used to 'displace' air in the space to give 'displacement' or 'piston flow' ventilation. These techniques give characteristically different pollutant profiles.

- Mixing Ventilation (MV)

  In MV, mixing is simulated by initial turbulence in the supply air and by the design of air supply diffusers. It is specially important when recirculation is used to provide thermal conditioning. If mixing is perfect, the pollutant concentration is uniform throughout the space. By using a high outlet velocity of supply air, the supply air is mixed with the ambient room air. The air that reaches the occupied zone is a mixture of supply and ambient air.

- Displacement Ventilation (DV)

  The principle of DV is to supply air with low velocity and low turbulence intensity at a low level in the room and exhaust it at a high level from the room. By supplying cold air to a room at floor level, a thermally stratified displacement system takes advantage of the natural tendency of this air to flow along the floor beneath the warmer air in the room. The cold air will rise by natural convection, being transported upwards at the heat sources (people and equipment) within the space. Because the heat sources in the space are usually the contaminant sources, the low turbulence of the airflow causes minimal mixing of the contaminants. Contaminants can be moved directly upwards, to be exhausted out of the space. Contaminants generally tend to stratify, much like the air does, thereby resulting in higher concentration in the cooler, cleaner air in the lower regions of the room than that for the same ventilation rate with a mixing system. The larger the temperature difference between air near the floor and air near the ceiling, better is the performance of these systems.

The spatial concentration of pollutants within the space is non-uniform, with air up-stream of the pollutant source being uncontaminated while the air down-stream of source may become heavily contaminated. Good design is aimed for ensuring the separation of occupants from polluted air. In practice some mixing inevitably occurs. Very careful airflow and temperature control is needed to inhibit mixing. Contaminants upstream of the occupied space or breathing zone must be avoided. Examples of such pollutants include floor level contaminants from floor coverings and carpets. DV is normally used in hotels, industries and hospitals etc..

1.5 Overview of Room air-conditioning

Proper distribution of conditioned air plays a vital role in energy savings, human comfort and maintenance of indoor air quality in air-conditioned spaces since the distributions of temperature, humidity and concentration of pollutants directly depends upon airflow pattern. The conditioned air should be supplied in sufficient quantity and at correct temperature and humidity so as to meet various thermal requirements of the space. Large air velocities and temperature gradients should be avoided since these may cause excessive noise apart from draft conditions, which are undesirable for human comfort. Upto 90% of a typical person's time is spent indoors and a large percentage is spent in residential or commercial environment. Quality of indoor air is an important component influencing our overall health and comfort.

Now-a-days very effective insulation materials are being used in air-conditioned buildings. This has considerably reduced the heating/cooling loads and thereby the volume flow rate of supply air required to remove these loads, has also been reduced considerably. Therefore *sick-building syndrome* has become an important phenomena which results from poor distribution of air, temperature and high contaminant concentrations due to low volume flow rates. This leads to thermal discomfort resulting in a significant loss in human efficiency and productivity. Competing requirements of energy conservation and better indoor air quality have made the search for effective ventilation system mandatory. IAQ may be improved by increasing the ventilation rate (fresh air), however, increase in ventilation rate results in higher energy costs. Recirculation with treated air may also not be economical. Indoor air pollution has emerged as an international issue. Increased awareness of potential health risks associated with indoor air pollutants has stimulated interest in improving our understanding of how pollutants are transported in buildings. Pollutant transportation and distribution depends upon the ventilation system, flow rate, the location of supply air outlet, return air inlet and diffuser characteristics. Another objective of air-conditioning system is to create a comfortable thermal environment with proper combination of comfort indices like velocity, temperature, relative humidity, temperature stratification, radiant temperature, asymmetry in radiant temperature, heat sources, turbulence intensity and dominant frequency of flow fluctuation apart from including the activity dependent metabolic rate and clothing *etc.*. Supply air velocity, temperature, volume flow rate, duct geometry, location and orientation of supply air outlets and return air inlets, characteristics of diffusers and room configuration have profound influence over the comfort indices.

The region between the ceiling and the occupied zone acts as entrainment zone which reduces the main jet velocity substantially by the time it reaches the occupied zone. The way the air diffuses into the occupied zone and the energy is convected by entrained flow and natural convection, is of prime importance in determining good air quality and comfort conditions.

Accurate predictions of distribution of velocity, temperature and concentration of pollutants *etc.* is indispensable for designing high quality air-conditioning system from the view point of comfort and acceptable indoor air quality.

A basic and long-standing problem in indoor air quality and environmental research is the lack of measurement techniques and instrumentation to qualitatively determine full-scale airflow in rooms. Difficulties include measurements of low air velocities, the direction of the velocities, high turbulent intensity, large open spaces, presence of human beings in stationary/moving position, furniture, heat sources and complicated geometry in buildings. For low velocity measurements, such as indoor airflow, buoyancy effect makes it difficult to use thermal based sensors. The thermal anemometers commercially available are designed for air velocities higher than 0.15 m/s, which is above the indoor air velocities in many occupied zones. The disturbance to the airflow field created by the physical obstruction of the instrumentation and the sensors themselves is difficult to evaluate. Laser doppler velocimetry (LDV) can accurately measure low velocity magnitude and direction without disturbance to the flow fields, but it can only measure one point at one time, and is expensive. For transient flows, point measurement results are difficult to interpret since the various spatial locations are sampled at different times and different flow conditions. For full-scale room measurements, LDV is difficult to set up. Some researchers have used LDV to measure velocity distribution in reduced scale model rooms.

For large buildings like atria, theatres, indoor stadium *etc.* one has to resort to dynamic and thermal similarity on reduced scale models. However, it is not possible to make Re and Ar equal for model and prototype concurrently. These gap results in the lack of good data to validate computer models for indoor airflow.

Therefore, non-intrusive, full scale and accurate measurement techniques for low speed airflow in rooms are needed. Particle image velocimetry (PIV), a technique that uses particles and their images to measure flow velocity, is a promising technology to meet the needs of room air studies. PIV measures a two-dimensional velocity vector map of a flow field at an instant of time by acquiring and processing images of particles seeded into the flow field. PIV technology needs to be developed for full-scale room. The application of PIV is very much hampered by the lack of sufficient number and homogeneous production, when helium-filled soap bubbles are used as tracer particles.

For the design of air-conditioning in conventional buildings, the design guides give sufficient information regarding sidewall, grilles, ceiling diffusers and other configurations of inlet and outlet along with their distribution characteristics. For non-conventional design, for example, rough surfaces, protrusions and obstructions like beams, light fittings, furniture and presence of human beings, all of which cause faster

(7) These terms have not been introduced. [illegible]

decay of jet, no design data is available. These designs require experimental inputs or numerical simulation. Also, the design guide data considers only global parameters. The supply air conditions, grille location and orientation may be correct but something may go wrong. Hence what is important is that what happens in the occupied zone, for this reason accurate prediction of distributions of various parameters is essential.

Numerical modeling has proved to be a successful tool for building design and air-conditioning engineers to understand the complex thermofluid phenomenon in buildings. These are ideally suited candidates for numerical simulation since it requires less time, less cost and less effort. The solution can be readily obtained and modified in a short span of time and helps the designer in choosing an optimum design from various alterations since it has the flexibility in dealing with boundary conditions and has the ability to provide an overview of flow field and distributions of flow parameters. The results can further be used for overall evaluation of indoor air quality and thermal environment in terms of ventilation efficiency and Percentage mean vote (PMV) for comfort. The solutions are usually obtained by iterative methods with large number of iterations hence rigorous validation procedures are required before the solution can be used for design with confidence.

From computational point of view, the evaluation of distributions of velocity, temperature and contaminants in the rooms is very complex. It consists of free jets near the supply air outlet with entrainment and shear layers, attachment, recirculation zones, wall jet and boundary layers along the walls. In reality, at reasonable ventilation rates, the flow is fully turbulent in the supply air ducts, HVAC outlets/inlets and downstream of the edges of the obstacles. Elsewhere, the flow is more likely to be laminar/weakly turbulent and unsteady with a wide range of small to large scale flow structures where the molecular transport is important. The turbulent modeling therefore poses challenging problems, in addition the modeling has to take care of the facts like, cold jet is stable above its centreline and unstable below the centreline, the temperature differences can cause plumes or down-drafts due to natural convection, turbulence in the cold air rising up will be damped and relaminarization may take place, stratified flow can be subcritical or supercritical. In general, turbulence is not isotropic therefore $k - \epsilon$ model may not yield good results. Hence laminar and low Reynolds number turbulent flow modeling is gaining increasing importance. In the context of heating (or cooling in warm climates), these flows are buoyant and in some cases, buoyancy drives the mean flow motion.

1.6 Indian climate

India has tropical weather. The Indian subcontinent has eight climatic zones all of which have only the monsoon rains in common. However, the monsoon comes to different parts of country at different times. And one can fly in the space of a couple of hours through a range of weather from the cold crisp air of the mountains to the burning dry heat of the Rajasthan Desert where summer temperature regularly reaches $45°C$ and beyond it.

Punjab, Haryana and other parts of western Uttar Pradesh suffer from drastic extremes in climate. It can be very cold from December to January, very dry and warm from the end of March till June and very warm and humid during the monsoon from July to September. The rest of the year is comfortably pleasant.

In central India, the summer months are an interminably warm. The temperature begin to rise in March and by May these hover around $45°C$. It has been observed that in a very few of major cities. the climate is cold. It is warm in most of the cities of Central India throughout the year. Therefore, in our country, air-conditioning with cooling is applicable in most of the region for human comfort. Air-conditioning with heating is required in the areas near the mountains in the northern part of the country. In a nutshell, it can be said that climatic conditions of India requires both, heating and cooling for comfort.

In this thesis, the following cases have been studied for laminar and turbulent flow.

- Room airflow with cooling;
- Room airflow with heating;
- Room airflow with occupancy.

Since the room airflows are complex in nature, they are neither laminar nor fully turbulent. At some places in the room specially near the inlet and obstacles, the air-flow is turbulent, elsewhere due to relaminarization it is weakly turbulent or laminar flow. Therefore one can not rely on the predictions of laminar flow only because the turbulent flows contain variations on a much wider range of length and time scales

([7]) than laminar flows. So even though they are similar to the laminar flow equations, the equations describing turbulent flows are usually much more difficult and expensive to solve.

The thesis consists of ten chapters with two appendices. Chapter 1 deals with the introduction of the room airflow, basic air-conditioning problem, control of indoor air pollutants, clean rooms, ventilation systems, overview of room air-conditioning and indian climate. Chapter 2 deals with the present status of the problem, literature review and scope of the present study. Chapter 3 describes the governing equations used for laminar/turbulent flow and selection of turbulence model. Chapter 4 describes the simulation methodology, boundary conditions and validation of computational model. Chapters 5, 6 and 7 illustrate the results and discussion for room airflow with cooling/heating with and without occupancy for different values of Re and Gr, inlet jet orientations for different room geometries. Experimental work for flow visualization is discussed and results are presented in chapter 8. The conclusions are presented in chapter 9. Chapter 10 suggests the scope of future work. Appendices A and B describe Boussinesq's approximation and calculation methods for obstacle boundary, special treatment for damping functions, global energy balance in a room, Nusselt number, Sherwood number, heat transfer rate and specification of velocity at the outlet.