ANALYSIS OF RADIATIVE HEAT TRANSFER IN AN ABSORBING-EMITTING-SCATTERING MEDIUM USING FLUENT

A THESIS SUBMITTED IN PARTIAL FULFILMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

in

Mechanical Engineering

By

SUMIT KUMAR

Department of Mechanical Engineering

National Institute of Technology

Rourkela

2011

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CERTIFICATE

This is to certify that the thesis entitled "**ANALYSIS OF RADIATIVE HEAT TRANSFER IN AN ABSORBING-EMITTING-SCATTERING MEDIUM USING FLUENT**" submitted by **SUMIT KUMAR** in partial fulfilment of the requirements for the award of Master of Technology Degree in Mechanical Engineering with specialization in **Thermal Engineering** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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M.Tech (Thermal Engineering)

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ABSTRACT

KEYWORDS: - (FLUENT, Linear anisotropic scattering, participating medium, Radiative heat transfer, Rayleigh scattering)

Thermal radiation is transferred by electromagnetic waves or photons. Thermal radiation is a very complex phenomenon and although the governing equations are known but they are difficult to solve. The analysis of radiative heat transfer in presence of participating medium is very difficult because radiative intensity as function of position, direction, wavelength, temperature and time. In some cases, these dependencies are not straightforward.The transient term of the radiative transfer equation (RTE) can be neglected i.e. steady-state RTE assumption does not lead to significant errors, since the temporal variations of the observables are in the range of 10^{-9} to 10^{-15}. The problem has been solved using the FLUENT software to analyze the radiative heat transfer problems, based on finite volume method (FVM). The available computational fluid dynamics software package FLUENT is applied to various test problems using DISCRETE ORDINATE MODEL (DOM MODEL) and the results obtained have been compared with other published results. The test problems include Isothermal Absorbing-Emitting medium in square enclosure, purely scattering medium in square and rectangular enclosure, three-dimensional heat generation in cuboid enclosure, collimated incidence in square enclosure, non-isothermal gray participating medium between two parallel surfaces and also anisotropically scattering gray planar medium in square enclosure. The medium is homogeneous and diffuse gray surface is used.The user defined function (UDF) has been written in C programming language for temperature profile, linear anisotropic phase function and Rayleigh phase function. The effect of absorption coefficient, scattering coefficient, scattering albedo, emissivity, anisotropic factor, grid size, angular discretization and angle of incidence on heat flux and temperature in the medium has been studied. The effect of Rayleigh phase function on heat flux has also studied.

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Nomenclature

a_1	anisotropic factor
c	speed of light, $3x10^8$ m/s
G	incident radiation, $\int_{4\pi} I d\Omega$
G^*	dimensionless G, G/ $(4\sigma T_b^4)$
I	intensity
I_b	blackbody intensity, $\sigma T^4/\pi$
k	thermal conductivity
M	number of discrete directions
$\hat{n}$	Outward normal of the control volume face
$\hat{n}_x$	Unit vector normal to the x= constant line
$\hat{n}_y$	Unit vector normal to the y= constant line
Q	heat flux, $\int_{2\pi} I(\hat{s}.\hat{n}_i) d\Omega$
p	radiation pressure tensor
q_c	heat flux due to collimated beam
q_{gen}	heat source
q^*	dimensionless heat flux, $q/\sigma T_g^4$
q^{**}	dimensionless heat flux, q/q_c
q^{***}	dimensionless heat flux, $q/\sigma(T_h^4 - T_c^4)$
S	source function
S_m'	modified source function

s distance traveled by a beam

$\hat{s}$ unit direction vector

u internal energy

v velocity vector

T temperature

t time

x, y, z coordinate directions

X nondimensional length, x/L_x

Y nondimensional length, y/L_y

ΔA area of control volume faces

Δv volume of control volume faces

Δx, Δy x and y direction control volume widths

Greek symbols

β extinction coefficient, κ + σ

β'_m modified extinction coefficient

$\Delta\Omega$ control angle

ε emissivity

θ polar angle

φ azimuthal angle

κ absorption coefficient

σ scattering coefficient or Stefan-Boltzmann constant

ρ density of the medium

Φ scattering phase function

Subscripts

b blackbody

c cold or collimated

E, W, N, S east, west, north and south neighbors of P

e ,w ,n, s east, west, north, and south control volume faces

g gas

h hot

P control volume

x ,y ,z coordinate directions

r reflectance

t transmittance

w wall/boundary

λ spectral

Superscripts

l ,l' angular directions

m index for the discrete direction

* dimensionless quantity

Chapter1

Introduction

- **General**
- **Objective of the Present work**

1.1 General

Thermal radiation is transferred by electromagnetic waves or photons, which may travel over a long distance without interacting with a medium. Thermal radiative energy consists of electromagnetic waves or photons. All electromagnetic waves or photons propagate through any medium at a speed of light. Thermal radiation is a very complex phenomenon and although the governing equations are known but they are difficult to solve. This difficulty is due to radiation intensity as a function of position, direction, wavelength and temperature. In some cases, these dependencies are not straightforward.

Conductive and convective heat transfer rates are linearly proportional to temperature differences but radiative heat transfer rates are proportional to differences in temperature to the fourth power.

Radiative transfer between surfaces that separated by vacuum or by transparent medium is known as radiatively nonparticipating medium whereas the interaction of thermal radiation with an absorbing, emitting and scattering medium is known as radiatively participating medium as shown in Fig. 1.1.

There are many industrial application of radiative heat transfer in participating medium such as furnaces, gas turbines, internal combustion engines, rocket propulsion, hypersonic shock layers, nuclear explosions, plasma in fusion reactors. In addition to industrial interest, radiation heat transfer is an effective parameter in the effect of dust, carbon dioxide and other participating gases on the environment.

Thermal radiation being part of electromagnetic spectrum travels with the speed of light. The speed of light is so large compared to local time scales and length scales that the transient term from the radiative transfer equation is neglected i.e. radiation is assumed to be an instantaneous(steady-state) process. The transient term of the radiative transfer equation (RTE) can be neglected i.e. steady-state RTE assumption does not lead to significant errors, since the temporal variations of the observables are in the range of 10^{-9} to 10^{-15}.

Radiative transfer equation is an integrao-differential equation involving seven independent variables:

1. The wavelength of radiation
2. Three space coordinates(x, y and z)
3. Two coordinates describing the direction of travel, polar angle and azimuthal angle(θ and φ)
4. time

Therefore its analytical analysis is very difficult. The various numerical methods have been used to solve the radiative transfer equation are the Monte Carlo method, the integral equation solution, the finite volume method (FVM), the radiation element method (REM), discrete transfer method (DTM) and the discrete ordinates method (DOM), flux method. All these methods have their advantage and disadvantage, and no one is considered as the best one for all applications. In the present work, we use the finite volume method (FVM).The finite-volume method (FVM) for radiation heat transfer is the discretization of equation by integration over both spatial control volume and angular control angle.

The advantage of modern computing capabilities, their dramatic reduction in cost and their widespread integration into the modern engineering design office have changed the way the design process is approached by the modern engineer. The availability of affordable high performance computing hardware and the introduction of user-friendly interface have led to the development of commercial CFD packages. Several general-purpose CFD package have been published in past decade. Prominent among them are PHOENICS, FLUENT, CFX and FLOW-3D.Most of them are based on the finite volume method. FLUENT is engineering simulation software, it contains the broad physical modelling capabilities needed to model flow, heat transfer etc. In present work, FLUENT software is used to simulate the radiative heat transfer in participating medium.

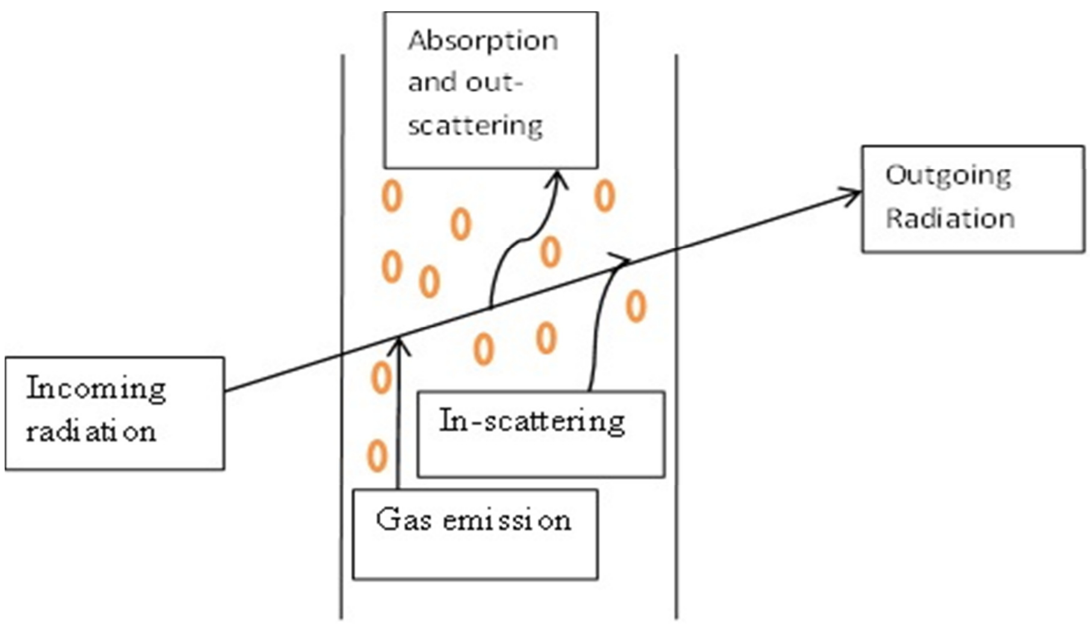


Figure 1.1 Radiative heat transfers in participating medium

1.2 Objective of the present work

- To Study the behaviour of radiative heat transfer in participating medium.
- To validate the result obtained with the help of FLUENT to other published results.
- To study the effect of absorption coefficient, scattering coefficient, scattering albedo, emissivity on the dimensionless heat flux and temperature.
- The study of the effect of linear anisotropic phase function and Rayleigh phase function on the dimensionless heat flux and temperature has not been done yet.
- The square enclosures is filled with isothermal medium or applied the temperature profile $T_g = T_{max} \times \exp(-y/L)$ into the medium. The effect of scattering albedo, linear anisotropic phase function and Rayleigh phase function will be studied.

Chapter 2

Literature Review

- **Introduction**
- **Literature**

2.1 Introduction

In recent year, the improvements in computer power have increased the interest of engineers and researchers to simulate their problems with computational methods. A lot of computational tools and methods have been developed in the last decades to analyse fluid dynamics, combustion, and different modes of heat transfer, which can be used in two- and three-dimensional configurations. Among other practical problems, one of the most important practical problems having highlighted role in the design and operation of high temperature industrial equipment, analysing radiative heat transfer in the participating media, has received considerable attention. Radiative heat transfer in the participating media that can absorb, emit and scatter radiation, and is usually surrounded by emitting, absorbing and reflecting walls, is a significant in many industrial applications, such as boilers, furnaces and jet engines. The analysis of radiative heat transfer in participating medium is very difficult, because the intensity is depends on wavelength, space coordinates, polar angle and azimuthal angle. Therefore many researchers has been developed the computational method such as finite volume method (FVM), discrete ordinate method (DOM), discrete transfer method (DTM), collapsed dimension method (CDM) etc.

2.2 Literature

Chai et al. [1] presented a finite volume method (FVM) for radiation heat transfer in absorbing, emitting and ansiotropically scattering media. The FVM is applied to six test problems; the test problems include two- and three-dimensional enclosures with participating media, collimated incidence, and heat generation. The efficiency of the FVM is also investigated using a three-dimensional test problem.

Spiga et al. [2] investigated radiative heat transfer through non-isothermal gray participating medium between two parallel surfaces kept at a fixed temperature; cold wall was diffuse while the hot wall was either diffuse or specular. The integro-differential transfer equations for surface reflection were solved in semianlytical form by projectional methods, conduction or convection was neglected. The heat flux and temperature distribution in the participating medium were calculated in each physical condition, in order to compare the effects of different reflection modes on heat transfer. The result show that temperature distributions and heat fluxes are only slightly affected by the particular reflection law, the relative difference being less than 1%.This suggest that diffuse reflection only should be considered for practical applications, since it requires a much simpler computational procedure.

Mishra e t al.[3] applied the collapsed dimension method(CDM) for radiative heat transfer in absorbing, emitting and anisotropically scattering medium in one-dimensional gray Cartesian enclosure, boundary emission and isothermal medium emission problems have been considered. These are representatives of radiative and non-radiative equilibrium cases respectively. The effects of scattering albedo, phase function anisotropy and bounding walls emissivity on non-dimensional wall heat flux for both types of problems have been investigated. For all the test cases, CDM results have been found to compare exceedingly well with the results of the benchmark methods.

Kim et al. [4] implemented the finite volume method (FVM) and the discrete ordinate method (DOM) to assess their capability to predict radiative heat transfer in a three-dimensional enclosure. A varying optical thickness and a nonuniform temperature profile are assumed to reproduce a typical furnace. Results show that the FVM performs better than the DOM in optically thin media, while they show comparable accuracy in optically thick media. The lower-order FVM and DOM may lead to erroneous results due to the ray effect in optically thin media with a highly nonuniform temperature profile.

Hassanzadeh et al. [5] applied the finite-volume method to the second-order radiative transfer equation which is proposed by Zhao and Liu, to study its accuracy and solution cost for two simple two-dimensional problems. The second-order equation leads to results that are accurate and bounded, but the iterative solution of the equations is expensive, especially for weakly participating media. The high cost is due mainly to the elliptic character of the second-order equation and the lack of diagonal dominance of the algebraic equations.

Kim et al.[6] applied FT_n FVM to absorbing,emitting and anisotropically scattering media with variable optical thickness in a rectangular enclosure.Results show that the FT_n FVM performs better than the discrete ordinate method(DOM) and the FVM with $N_\theta \times N_\Phi$ uniform angular discretization except near the optically thick diffusion limit. It also turns out that anisotropic scattering has significant influence on radiative heat transfer with a symmetric boundary condition in a moderate optical thickness range as well as with a nonsymmetric boundary condition.

Baek et al. [7] applied the finite volume method for radiation to analyse the rocket plume base heating.The exhaust plume is considered to absorb,emit and scatter radiant energy isotropically as well as anisotropically,but the medium in the environment is not participating.The scattering phase function is modeled by a finite series of Legendre polynomials.Validated the results with the previous results obtained by the Monte-Carlo method,further investigations have been done by changing various parameter,such as plume cone angle,scattering albedo,scattering phase function,optical radius and nozzle exit temperature.The results show that the base plane is predominantly heated by the plume emission,rather than the searchlight emission,when the nozzle exit temperature is the same as that of plume.

Coelho [8] presented the fundamentals of a new radiation model in which the spatial and angular dependence of the radiation intensity are split in such a way that the radiation intensity is approximated by a linear combination of basic functions dependent only on the angular direction. The coefficients of the approximation are functions of the spatial coordinates. The spatial discretization is performed using the finite volume method and the angular discretization is based on the finite element method. The step scheme was employed in the spatial discretization and bilinear basis functions were chosen for the angular discretization. The method may be applied to both grey and non-grey media, non-scattering and scattering media, simple and complex geometries. It is applied simple one-dimensional problems of radiative transfer in enclosures with grey, emitting-absorbing and scattering media. The results obtained show that the method gives good results for several benchmark problems with available analytical solutions, and converges to the exact solution as the grid is refined and the number of terms in the approximation increases.

Mohamad [9] presented a local analytical method as an alternative method of solution of the discrete-ordinate radiative transfer equations instead of the conventional finite difference method. The method is based on analytical solution of a multidimensional, linearized equation .It is more accurate than linear-interpolation of the intensity within each control volume. Conventional solution (diamond differencing) of the discrete ordinate method (DOM) may lead to negative fluxes, which is physically unacceptable. This method (local analytical discrete ordinate method, LADOM) does not suffer from such a problem. The predictions of LADOM are well compared with that of zonal and conventional finite-difference methods. This method is more accurate, free from oscillation and simpler to apply to multi-dimensional problems than the conventional finite-difference method.

Trivic et al. [10] developed a new mathematical model and code for radiative heat transfer of particulate media with anisotropic scattering for 2-D rectangular enclosure. The model is based on the coupling of (i) finite volume method for the solution of radiative transfer equation with (ii) Mie equations for the evaluation of scattering phase function. For those results the S-N discrete ordinates method for the solution of radiative transfer equation and the Legendre polynomials expansions for the evaluation of scattering phase function were used. The new model was applied to the solid particles of several various coals and of an ash and the series of 2-D predictions are performed. The effects of particle size parameter and of scattering albedo on radiative heat flux and on incident radiation were analyzed. It was found that the model developed is reliable and very accurate and thus suitable for extension towards: (i) 3-D geometries, (ii) mixtures of non-gray gases with particles as well as for (iii) incorporation in computational fluid dynamics codes.

Sun et al. [11] developed an alternative form of Tan's formulation to describe thermal radiation problems in a gray, absorbing, emitting and isotropic scattering medium bounded by a gray and diffusely emitting and reflecting enclosure. The radiosity algorithm was adopted in the governing equations. A modified boundary element method was developed to solve the equations. A group of cases was studied. The modified boundary element method was found to be effective and accurate in treating general thermal radiation problems.

Wu et al. [12] applied the integral equation method to study radiative transfer in a two dimensional cylindrical medium exposed to collimated radiation. They validate this work to existing results. The effects of parameters, such as the aspect ratio, the optical thickness and the scattering albedo, are investigated.

Maruyama et al. [13] analyzed radiative heat transfer of absorbing, emitting and scattering media and of diffuse and specular surfaces by a generalized numerical method: radiation element method by ray emission model (REM). Arbitrary thermal conditions can be specified for each radiation element. A generalized radiative heat transfer analysis can be achieved without recognizing participating media and surface elements by introducing the ray emission model and extinction, absorbing and diffuse scattering view factors. Torus plasma in a large helical device for the research of a fusion reactor is analyzed, in which plasma is approximated as a gray participating medium and a specular and diffuse surface is assumed for the vacuum chamber. They presented the dimensionless temperature distribution of the modeled plasma and the dimensionless surface heat flux distribution on the wall of the vacuum chamber.

Mishra et al. [14] proposed a new formulation of the collapsed dimension method (CDM), called the modified collapsed dimension method (MCDM) whose approach is similar to the discrete ordinate method (DOM). In the MCDM, the time consuming procedures of ray tracing and source term evaluation are not required, as a result of which the method becomes computationally efficient. They considered test problems dealing with radiative heat transfer with absorbing, emitting and scattering medium. They compare the performance of the MCDM; the same problems have also been solved using the CDM and the DOM. For the same level of accuracy, MCDM has been found faster than the CDM and the DOM.

Talukdar [15] implemented a blocked-off region procedure with the collapsed dimension method (CDM) to deal with radiative transport problems in irregular geometries. Different test problems are validated for radiative and non-radiative equilibrium situations in participating or nonparticipating media. Results are found to be satisfactory for all straight edged, inclined and curved boundaries. The blocked-off region procedure based on Cartesian coordinate is found to be very convenient for a ray-tracing method like the CDM. The same ray tracing algorithm for a rectangular enclosure could be effectively used for any kind of 2-D geometries. This significantly reduces the effort of developing different ray-tracing algorithm for different geometries. In addition, it is an alternative than to write an algorithm in curvilinear coordinate for irregular geometries which found to be complicated for a ray-tracing method like the CDM.

Kim [16] investigated the radiative heat transfer in an axisymmetric enclosure containing an absorbing, emitting, and scattering gray medium by using the finite volume method (FVM). By considering the three-dimensional procedure, the angular redistribution term, which appears in such curvilinear coordinates as axisymmetric and spherically symmetric ones, can be treated efficiently without any artifice usually introduced in the conventional discrete ordinates method (DOM). After a mathematical formulation and corresponding discretization equation for the radiative transfer equation (RTE) are derived, final discretization equation is introduced by using the directional weight, which is the key parameter in the FVM since it represents the inflow or outflow of radiant energy across the control volume faces depending on its sign. The present approach is then validated by comparing the present results with those of previous works. All the results presented in this work show that the present method is accurate and valuable for the analysis of cylindrically axisymmetric radiative heat transfer problems.

Wang et al. [17] presented a meshless method to solve the radiative transfer equation in complex 2D and 3D geometries. In order to avoid numerical oscillations, the even parity formulation of the discrete ordinates method is used. A moving least squares approximation meshless method is used to solve the second order partial differential equations. Prediction results of radiative heat transfer problems obtained by the proposed method are compared with reference in order to assess the correctness of the present method.

Salah et al.[18] solved the radiative transfer equation by the finite-volume method in an axisymmetric two-dimensional geometry with absorbing, emitting, and either isotropically or anisotropically scattering gray medium. Explicit expressions of the coefficients appearing in the discretized angular redistribution term have been determined. These coefficients verify the recursive relation established by Carlson and Lathrop and lead to accurate numerical results.

Yuen et al. [19] presented superposition of fundamental solutions to find temperature and heat flux distributions in gray walled two-dimensional rectangular enclosures with a gray absorbing, emitting, isotropically scattering medium. The fundamental solutions are temperature and heat flux distributions for enclosures with black boundaries and a step change in temperature over a finite wall interval. They are found using a variation of the conventional zonal method. Based on these results, the effects of surface boundary conditions on the temperature distribution and heat transfer are discussed.

Krishnpraksh[20] analyzed the problem of one dimensional plane-parallel absorbing,emitting and isotropically scattering gray slab with gray,diffusely emitting and specularly reflecting boundaries,under the condition of radiative equlibrium. The governing energy equation which is a Fredholm integral equation of the second kind involving the integral functios $C_n(t)$ is solved by an accurate modified quadrature method based on Gauss-Legendre rule.The temperature distribution and heat flux results are presented. A three term exponential curve fit is presented to represent the heat transfer result of diffusely reflecting boundaries case.

Godoy et al.[21] analyzed for 3D enclosures for cases in which the intensities are strongly coupled to each other such as: radiative equilibrium and scattering media. A Newton–Krylov iterative method (GMRES) solves the final systems of linear equations along with a domain decomposition strategy for parallel computation using message passing libraries in a distributed memory system. Results are presented for the DOM-integrated quantities such as heat flux, irradiation and emission.A variety of flux limiters are compared to ‘‘exact” solutions available in the literature, such as the integral solution of the RTE for pure absorbing-emitting media and isotropic scattering cases and a Monte Carlo solution for a forward scattering case. Additionally, a non-homogeneous 3D enclosure is included to extend the use of flux limiters to more practical cases. The overall balance of convergence, accuracy, speed and stability using flux limiters is shown to be superior compared to step schemes for any test case.

Byun et al.[22] proposed a combined procedure of the Monte-Carlo and finite-volume method (CMCFVM) for solving radiative heat transfer in absorbing, emitting, and anisotropically scattering medium to eliminate the wiggling behavior. To tackle the ray effect problem, which is especially pronounced in a medium with an isolated boundary heat source, the CMCFVM is suggested here and successfully applied to a two-dimensional irregular geometry.

Zhao et al.[23] developed the least-squares spectral element method based on the discrete-ordinate equation to solve multidimensional radiative heat transfer problems in semitransparent media. Chebyshev polynomials are employed as basis functions for the spectral element discretization. The convergence rate is very fast and approximately follows the exponential law. Four test problems are taken as examples to verify the least-squares spectral element formulation. The predicted temperature distributions and radiative heat flux are determined by the least-squares spectral element method and compared with data in the references. The results show that the least-squares spectral element method developed in this article has good accuracy for solving multidimensional radiative heat transfer problems.

PARK et al.[24] applied the modified differential approximation (MDA) first proposed by Olfe and recently extended by Modest to a three-dimensional absorbing-emitting-scattering medium bounded by non-black walls. Numerical techniques are developed to solve for the radiation fields due to wall emission and medium emission. The techniques are evaluated in terms of the computer memory requirement. CPU time and numerical accuracy. For a model problem, the modified differential approximation is compared against the zone method, the

P_1, approximation, the P_3 approximation, S_4 and S_6. MDA is shown to be superior to the P_1 and P_3 approximations and to compare favorably with SN solutions for all conditions of optical depth.

Kim et al.[25] studied radiative heat transfer in an axisymmetric enclosure with absorbing, emitting, and scattering medium using the different methods such as MDOM, FVM, and MFVM with emphasis on the treatment of angular derivative term, which appears in curvilinear coordinates due to angular redistribution. After final discretization equation for MFVM is introduced by using the step scheme and directional weights, the present approach is validated by applying it to three different benchmarking problems with absorbing, emitting, and scattering medium. All of the results presented here support its accuracy as well as moderate efficiency.Finally, the present approaches are applied to a truncated cone-shaped enclosure as a body-fitted geometry case.

Zhao et al.[26] developed the second-order radiative transfer equation , which is a diffusion-type equation similar to the heat conduction equation for an anisotropic medium. The consistency of the second-order radiative transfer equation with the original radiative transfer equation is demonstrated. The perturbation characteristics of error are analyzed and compared for both the first- and second-order equations. Good numerical properties are found for the second-order radiative transfer equation. To show the properties of the numerical solution, the standard Galerkin finite-element method is employed to solve the second-order radiative transfer equation. Four test problems are taken as examples to check the numerical properties of the second-order radiative transfer equation. The results show that the standard Galerkin finite-element solution of the second-order radiative transfer equation is numerically stable, efficient, and accurate.

Kim et al.[27] investigated the radiative heat transfer between two concentric spheres separated by an absorbing, emitting, and isotropically scattering gray medium using the finite volume method (FVM). By adopting the mapping process, angular redistribution, which appears in such curvilinear coordinates as cylindrical or spherical ones, is treated efficiently without any artifice usually introduced in the conventional discrete ordinates method (DOM). After a mathematical formulation and corresponding discretization equation for the radiative transfer equation (RTE) are derived,.The present approach is then validated by comparing the present results with those of previous works by changing such various parameters as temperature ratio between inner and outer spherical enclosure, wall emissivity, and optical thickness of the participating medium. All the results show that the present method is accurate and valuable for the analysis of spherically symmetric radiative heat transfer problems between two concentric spheres.

Mishra et al.[28] evaluated the collapsed dimension method (CDM) and the discrete transfer method (DTM) in terms of computational time and their abilities to provide accurate results in solving radiation and/or conduction mode problems in a 2-D rectangular enclosure containing an absorbing, emitting and scattering medium. The alternating direction implicit scheme was used for the solution of the finite difference part of the energy equation. For the three types of problems considered, tests were performed for a wide range of aspect ratio, extinction coefficient, scattering albedo, conduction–radiation parameter and boundary emissivity. For pure radiation problems, results from the two methods were validated against the results from the Monte Carlo method. For the combined mode, some steady-state results were compared with results available in the literature. For the transient situations, results from the two methods were validated against each other. While both the methods were found to give the same results, the CDM was found to be much more economical than the DTM.

Mishra et al.[29] applied the collapsed dimension method (CDM) to radiative heat transfer problems in a participating medium subjected to a continuous diffuse or a continuous/short-pulse collimated boundary radiative loading. The planar medium contained between diffuse gray boundaries is absorbing, emitting and anisotropically scattering.With three categories of thermal boundary radiative loadings, for the four types of problems considered, the CDM results are compared for a wide range of radiative parameters with that of the FVM.

Kim et al.[30] proposed a hybrid spatial differencing scheme for the discrete ordinates method to predict radiation intensity in a two-dimensional rectangular enclosure. Since the hybrid scheme incorporates the strengths from the diamond scheme and the step scheme, and takes into consideration the characteristics of the medium, it is more accurate and yields more stable results. Several other spatial differencing schemes are examined to address the effect of numerical smearing (or false scattering). Predictions from the present hybrid scheme are compared to those of the other schemes for transparent, purely absorbing, purely scattering, and absorbing-emitting-isotropically scattering media.It is found that the proposed scheme predicts more stable and less smeared results than the others.

Cumber[31] exmined the discrete transfer method developed by Lockwood and Shah for calculating radiative heat transfer is examined.Various aspects of the algorithm are analysed and modifications suggested to improve the accuracy and computational performance.These modifications are evaluated by comparing predicted heat fluxes with analytic and numerically accurate solutions to test problems and measured fluxes from experiments.The evaluation study shows the modifications yield significant improvements over the original algorithm.

Chapter 3

Mathematical Formulation

- **Introduction**
- **Basic Terms**
- **Radiative transfer equation**
- **Overall energy conversion**
- **Finite volume method**
- **Formulation of the discretization equation**

3.1 Introduction

This section is divided into five parts. Section 3.2 gives basic ideas [32], [33] to understand the term used in radiative heat transfer. The governing equation of radiative heat transfer in participating medium is given in section 3.3 .The overall energy conservation equation is combination of all three modes of heat transfer given in section 3.4.The finite volume method describe in section 3.5.Formulation of the discretization equation and solution procedure is given in section 3.6.

3.2Basic terms

3.2.1 Radiative Intensity

Radiative intensity is defined as radiative energy flow per unit solid angle and unit area normal to the rays. There are two types of intensity:

1. The spectral intensity refers to radiation in an interval $d\lambda$ around a single wavelength,
2. The total intensity refers to the combined radiation including all wavelengths.

The total intensity is the integral of the spectral intensity over all wavelengths

$$I(r, \hat{s}) = \int_0^\infty I_\lambda\,(r, \hat{s}, \lambda)d\lambda$$

3.2.2 Radiative heat flux

Radiative heat flux is the rate of radiation heat transfer through the control surface.

The total radiative heat flux is

$$q \cdot \hat{n} = \int_0^\infty q_\lambda \cdot \hat{n} d\lambda = \int_0^\infty \int_{4\pi} I_\lambda(\hat{s})\hat{n} \cdot \hat{s}\, d\Omega d\lambda$$

3.2.3 Absorption coefficient

Absorption coefficient is the property of medium that describes the amount of absorption of thermal radiation per unit path length within the medium. It can be interpreted as the inverse of the mean free path that a photon will travel before being absorbed (if the absorption coefficient does not vary along the path).The unit of absorption coefficient is per meter.

3.2.4 Scattering coefficient

Scattering coefficient is the property of a medium that describes the amount of scattering of thermal radiation per unit path length for propagation in the medium. It can be interpreted as the inverse of the mean free path that a photon will travel before undergoing scattering (if the scattering coefficient does not vary along the path).The unit of scattering coefficient is per meter.

3.2.5 Extinction coefficient

Extinction coefficient is the sum of absorption coefficient and scattering coefficient.

$\beta=\sigma + \kappa$

3.2.6 Scattering albedo

Scattering albedo is defined as the ratio of scattering coefficient to the extinction coefficient.

$\omega=\sigma/\beta=\sigma/ (\sigma + \kappa)$

Its value is lies between 0 and 1.When scattering albedo is zero means purely absorbing-emitting, when scattering albedo is unity means purely scattering.

3.2.7 Optical thickness

Optical depth, or optical thickness is a measure of transparency, and is defined as the negative logarithm of the fraction of radiation (e.g., light) that is not scattered or absorbed on a path. The optical depth is a measure of the proportion of radiation absorbed or scattered along a path through a partially transparent medium; the optical depth to a close-by object is zero; as the distance to the object increases, so does the optical depth. The optical depth expresses the quantity of light removed from a beam by scattering or absorption during its path through a medium. If I_0 is the intensity of radiation at the source and I is the observed intensity after a given path, then optical depth τ is defined by the following equation

$I_0/ I=e^{-\tau}$

If τ>>1, the path in the medium is optically thick. If τ<<1, the path in the medium is optically thin and the mean penetration distance is much larger than the path length; radiation can then pass entirely through the path length without appreciable extinction.

3.2.8 Refractive index

Refractive index is a non-dimensional parameter defined as the ratio of the speed of light in vacuum to that in a material.

$n=c_0/c$

Where $c_0=2.998\times10^8$ m/s

The refractive index of vacuum is n=1.For most gases the refractive index is very close to unity, for example air at room temperature has n=1.00029 over the visible spectrum. Therefore, light propagates through gases nearly as fast as through vacuum.

3.2.9 Scattering phase function

The scattering phase function Φ describes the probability that a ray from one direction $\hat{s}'$,will be scattered into a certain other direction, $\hat{s}$.Scattering phase function can be classified into two categories. These are linear anisotropic phase function and Rayleigh phase function. The linear anisotropic phase function is further divided into isotropic scattering and anisotropic scattering. Isotropic scattering scatters energy equally into all directions. Anisotropic scattering can be further divided into backward and forward scattering. Backward scatters more energy into the backward direction, while forward scattering scatters more energy into the forward directions.

Scattering phase function satisfies the following relation:

$$\int_{4\pi} \emptyset(\hat{s}', \hat{s}) \mathrm{dd}\Omega' = 4\pi$$

Where $\hat{s}'$ is the direction from which intensity is scattered into a direction $\hat{s}$.

3.2.10 Rayleigh scattering

The scattered energy in any direction is proportional to the inverse fourth power of the radiation wavelength. Rayleigh scattering is a limiting case when the scattering particle diameter is considerably smaller than the wavelength of the radiation within the particle. This type of scattering is important in the atmosphere, where scattering is by gas molecules. Rayleigh scattering by molecules of the atmosphere accounts for the background of the sky being blue and for the sun appearing red at sunset.

3.2.11 Radiative equilibrium

Radiative equilibrium means that thermodynamic equilibrium within the medium is achieved by virtue of thermal radiation alone, neglecting conduction and convection.

3.2.12 Diffuse-gray surface

Diffuse signifies that the directional emissivity and directional absorptivity do not depend on direction. The term gray signifies that the spectral emissivity and absorptivity do not depend on wavelength. They can depend on temperature.

The diffuse-gray surface absorbs a fixed fraction of incident radiation from any direction and at any wavelength. It emits radiation that is a fixed fraction of blackbody radiation for all direction and all wavelengths.

3.3 Radiative transfer equation (RTE)

A light beam traveling through a participating medium in the direction of $\hat{s}$ loses energy by absorption and scattering away from the direction of travel. But at the same time it also gains energy by emission as well as by scattering from other direction into the direction of travel $\hat{s}$.

3.3.1 Absorption

The absolute amount of absorption is directly proportional to the magnitude of the incident energy as well as the distance the beam travels through the medium.

$$dI = -\kappa I ds \quad (1)$$

3.3.2 Out-scattering

Attenuation by scattering or out-scattering is a part of the incoming intensity is removed from the direction of propagation $\hat{s}$. It is same as absorption but only difference is that absorbed energy is converted into internal energy while scattered energy is simply redirected along another direction.

$$dI = -\sigma I ds \quad (2)$$

3.3.3 Emission

The rate of emission from a volume element is proportional to the magnitude of the volume. So the emitted intensity is proportional to the length of the path and local energy content in the medium. At the thermodynamic equilibrium intensity everywhere will be equal to blackbody intensity.

$$dI = \kappa I_b ds \quad (3)$$

3.3.4 In-scattering

It has contribution from all the directions and hence must be calculated by integration over all solid angles, considering the radiative heat flux impinging on a volume element from an infinitesimal pencil of rays in a specified direction.

$$dI(\hat{s}) = ds\frac{\sigma}{4\pi}\int_{4\pi} I(\hat{s}')\, \emptyset(\hat{s}',\hat{s})d\Omega' \quad \text{.........} (4)$$

Making an energy balance on the radiative energy traveling in the direction of $\hat{s}$ .The change in the intensity is found by summing all contribution from emission, absorption, out-scattering and in-scattering

$$I(s + ds, \hat{s}, t + dt) - I(s, \hat{s}, t) =$$

$$\kappa I_b(s,t)ds - \kappa I(s,\hat{s},t)ds - \sigma I(s,\hat{s},t)ds + \frac{\sigma}{4\pi}\int_{4\pi} I(\hat{s}')\, \emptyset(\hat{s}',\hat{s})d\Omega' ds \quad \text{.........} (5)$$

Expanding the left side of the above equation using Taylor's Series and truncating after the first term we would the following equation as

$$\frac{1}{c}\frac{\partial I}{\partial t} + \frac{\partial I}{\partial s} = \kappa I_b - \kappa I - \sigma I + \frac{\sigma}{4\pi}\int_{4\pi} I(\hat{s}')\, \emptyset(\hat{s}',\hat{s})d\Omega' \quad \text{.........} (6)$$

The above equation is known as radiative transfer equation.

The speed of light is so large compared to local time and length scales that the first term in equation (6) may be neglected.

$$\frac{\partial I}{\partial s} = \kappa I_b - \kappa I - \sigma I + \frac{\sigma}{4\pi}\int_{4\pi} I(\hat{s}')\, \emptyset(\hat{s}',\hat{s})d\Omega' \quad \text{.........} (7)$$

The above equation is known as steady state radiative heat transfer.

3.4 Overall energy conservation equation

Thermal radiation is one of the modes of heat transfer and must compete with conduction and convection. So the temperature field depends on all the three modes of heat transfer.

The general form of the energy equation is:

$$\rho \frac{Du}{Dt} = -\nabla \cdot q - p\nabla \cdot v + \mu\varphi + q_{gen} \quad (8)$$

As the medium is radiatively participating through emission, absorption and scattering so the second and third effect is negligible. Assuming $u=c_v dT$ and Fourier's law of conduction to holds

$$q = q_c + q_r = -k\nabla T + q_r$$

In the absence of the heat generation

$$\rho c_v \frac{DT}{Dt} = \nabla \cdot (k\nabla T) - \nabla \cdot q_r$$

3.5 Finite volume method(FVM)

The finite volume method is a method for representing and evaluating partial differential equations in the form of algebraic equations .Similar to the finite difference method or finite element method, values are calculated at discrete places on a meshed geometry. "Finite volume" refers to the small volume surrounding each node point on a mesh. In the finite volume method, volume integrals in a partial differential equation that contain a divergence term are converted to surface integrals, using the divergence theorem. These terms are then evaluated as fluxes at the surfaces of each finite volume. Because the flux entering a given volume is identical to that leaving the adjacent volume, these methods are conservative. Another advantage of the finite volume method is that it is easily formulated to allow for unstructured meshes.

Typical two-dimensional Cartesian control volumes are shown in Fig. 3.1. The control volume interface is subdivided into four place faces for two-dimensional problem, which are denoted by lower case letters- *e*, *w*, *n*, and *s* corresponding to their direction along east, west, north and south respectively with respect to the central node *P*. Similarly, the adjacent control volume nodes are denoted by capital letters *E*, *W*, *N*, and *S* corresponding to their direction with respect to the central node *P*. There are various Radiations modelling technique like Monte Carlo method, Integral equation solution, Discrete transfer method, discrete order method but in this study Finite Volume method is used because FVM yield more accurate result and this method is fully conservative.

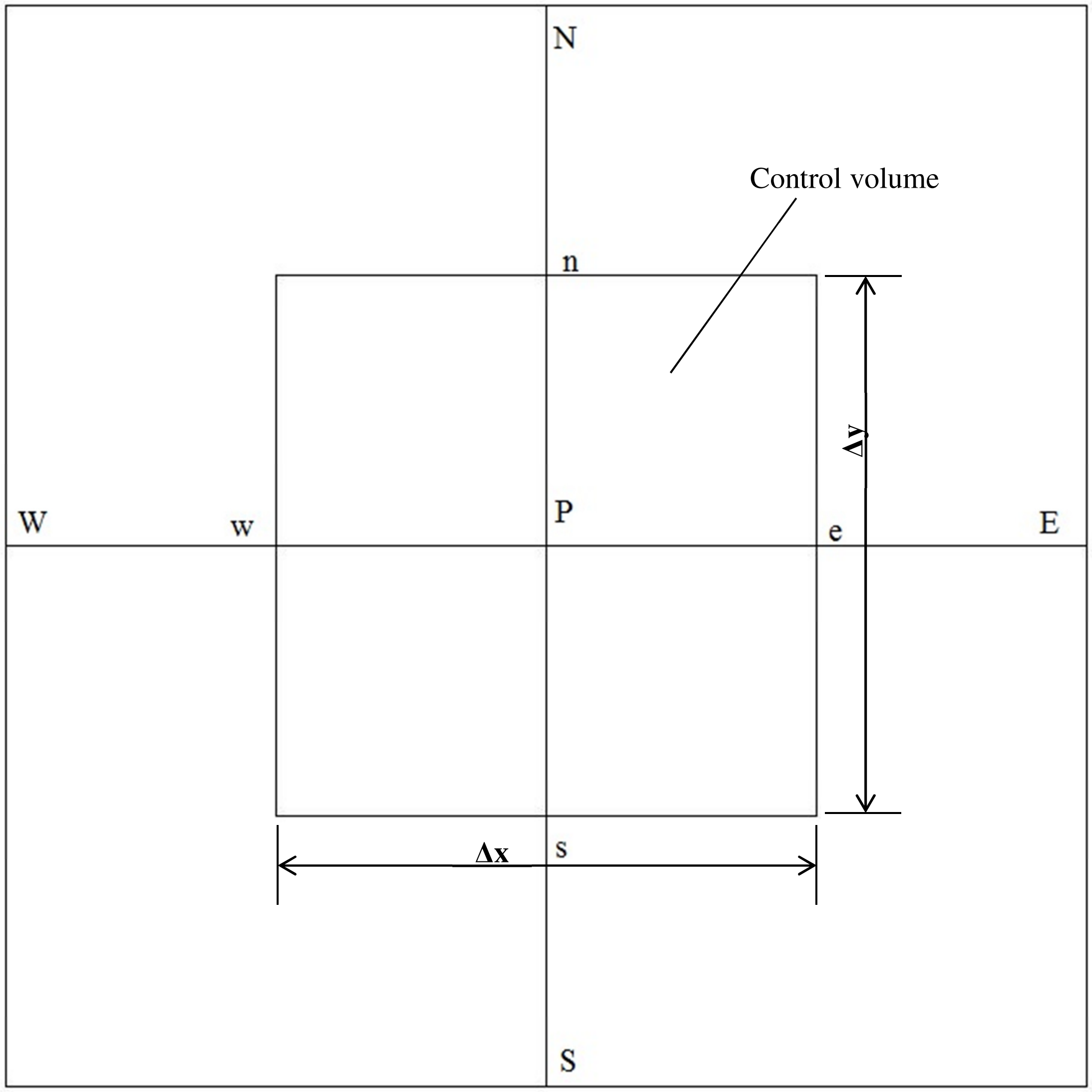


Figure 3.1 Two-dimensional control volumes with specified notations

3.6 Formulation of the discretization equation

Consider a square enclosure with black wall is filled with absorbing-emitting-scattering medium as shown in Fig 3.2. The computational domain is discretized in both spatially and angular direction as shown in Fig.3.1 and 3.3 respectively, then integrating the steady state radiative transfer equation over a control volume dV and control angle dΩ.

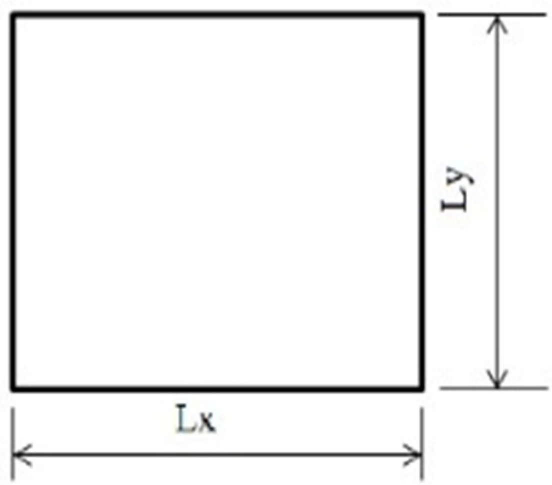


Figure 3.2 square enclosure

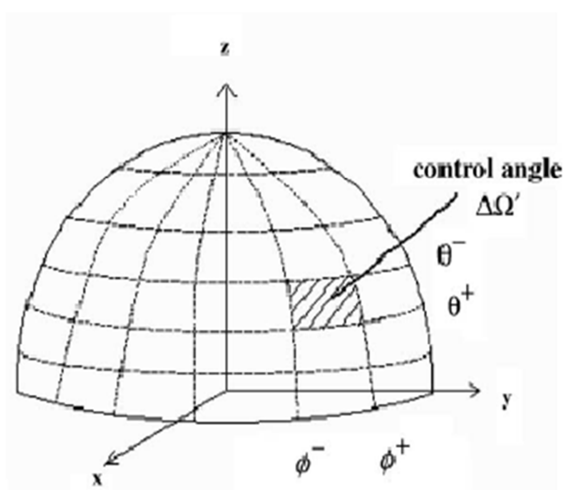


Figure 3.3 Control angle discretization in Finite Volume method

From equation (7), we get

$$\frac{\partial \mathrm{I}}{\partial \mathrm{s}} = \kappa \mathrm{I_b} - \kappa \mathrm{I} - \sigma \mathrm{I} + \frac{\sigma}{4\pi}\int_{4\pi} \mathrm{I}(\hat{\mathrm{s}}')\, \emptyset(\hat{\mathrm{s}}',\hat{\mathrm{s}})\mathrm{d}\Omega'$$

In terms of extinction coefficient and source terms, the radiative heat transfer equation becomes

$\frac{\mathrm{dI}}{\mathrm{ds}} = -\beta \mathrm{I} + \mathrm{S}$ ……………………………………………………………………..… (9)

Where Source term $\mathrm{S} = \kappa \mathrm{I_b} + \frac{\sigma}{4\pi}\int_{4\pi} \mathrm{I}(\hat{\mathrm{s}}')\Phi(\hat{\mathrm{s}}',\hat{\mathrm{s}})\mathrm{d}\Omega'$

Integrating eq. (9), we get

$\int_{\mathrm{d}\Omega'}\int_{\Delta \mathrm{v}} \frac{\mathrm{dI}'}{\mathrm{ds}} \mathrm{dvd}\Omega' = \int_{\mathrm{d}\Omega'}\int_{\Delta \mathrm{v}} (-\beta \mathrm{I}' + \mathrm{S}')\, \mathrm{dvd}\Omega'$…………………………………………....... (10)

Applying the divergence theorem eq. (10) becomes

$\int_{\mathrm{d}\Omega'}\int_{\Delta \mathrm{v}} \mathrm{I}'(\hat{\mathrm{s}}'.\hat{\mathrm{n}}) = \int_{\mathrm{d}\Omega'}\int_{\Delta \mathrm{v}} (-\beta \mathrm{I}' + \mathrm{S}')\, \mathrm{dvd}\Omega'$ …………………………………….…...... (11)

The control volume approach, the intensity is assumed constant within a control volume and control angle. Under these assumption eq. (11) can be simplified to

$\sum_{i=1}^{4} I_i' \,\Delta A_i \int_{d\Omega'} (\hat{s}'.\hat{n})\, d\Omega' = (-\beta I' + S')\Delta v \Delta\Omega'$ .... (12)

Where $S' = \kappa I_b + \frac{\sigma}{4\pi}\sum_{r=1}^{M} I^r\, \Phi^{r\prime}\Delta\Omega^{\mathrm{r}}$

The modified extinction coefficient and a modified source function can be written for a discrete direction l as

$\beta_m' = \beta - \frac{\sigma}{4\pi}\Phi''\Delta\Omega'$

$S_m' = \kappa I_b + \frac{\sigma}{4\pi}\sum_{r=1, r\neq i}^{M} I^r\, \Phi^{r\prime}\Delta\Omega^{\mathrm{r}}$

With this modification eq. (12) becomes

$\sum_{\mathrm{i}=1}^{4} \mathrm{I_i'}\, \Delta \mathrm{A_i} \int_{\Delta\Omega'} (\hat{\mathrm{s}}'.\hat{\mathrm{n}})\, \mathrm{d}\Omega' = (-\beta_{\mathrm{m}}' \mathrm{I}' + \mathrm{S_m'})\, \Delta \mathrm{v} \Delta\Omega'$ ……………………………………..... (13)

On further simplification, for a control volume and a control angle the equation becomes

$$(I'_e - I'_w)\Delta A_x D'_{cx} + (I'_n - I'_s)\Delta A_y D'_{cy} = -(\beta'_m)_p I'_p \Delta v \Delta\Omega' + (S'_m)_p \Delta v \Delta\Omega' \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Where $D'_{cx} = \int_{\Delta\Omega'} (\hat{s}'.\hat{n}_x)\, d\Omega', D'_{cy} = \int_{\Delta\Omega'} (\hat{s}'.\hat{n}_y)\, d\Omega'$

$$\Delta A_x = \Delta y \Delta, A_y = \Delta x, \Delta v = \Delta x \Delta y$$

$$\Delta\Omega' = \int_{\phi'-}^{\phi'+} \int_{\theta'-}^{\theta'+} \sin\theta \, d\theta \, d\phi$$

Using **Step** spatial differencing scheme as shown in Fig.3.4 (which sets the downstream boundary intensities equal to the upstream nodal intensities)

$$I_P^l = I_e^l = I_n^l, I_s^l = I_S^l, I_w^l = I_W^l$$

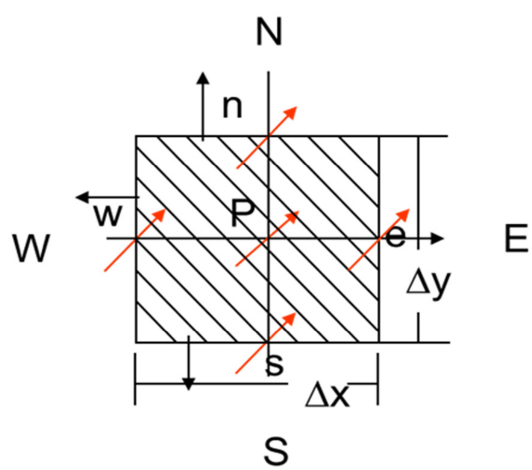


Figure 3.4 Step Scheme for a control volume

The discretized equation can be written in the following form

$$a_p^l I_p^l = a_W^l I_W^l + a_S^l I_S^l + b$$

Where $a_W^l = \Delta y D_{cx}^l, a_S^l = \Delta x D_{cy}^l, a_p^l = \left[\Delta x D_{cy}^l + \Delta y D_{cx}^l + (\beta_m^l)_p \Delta v \Delta\Omega^l\right], b = (S_m^l)_p \Delta v \Delta\Omega^l$

The flow chart for solving the discretization equation is given below

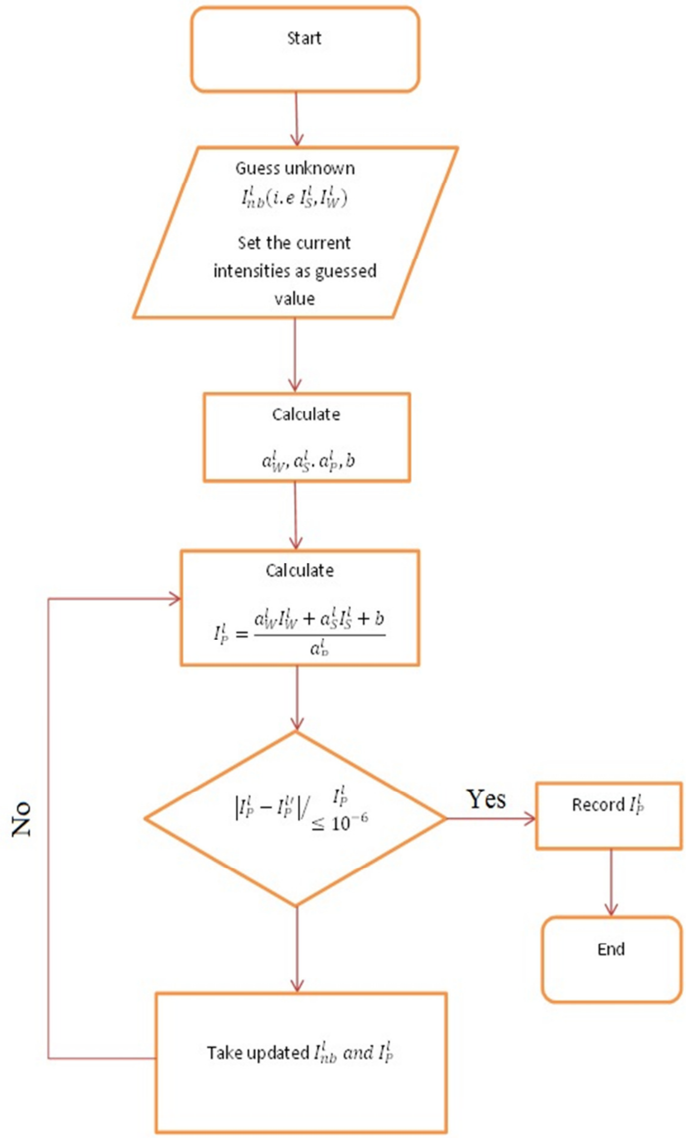


Figure 3.5 Flow chart

Chapter 4

Numerical Solution

- **Introduction**
- **Radiation Modal**
- **Problem solving steps**

4.1 Introduction

The availability of affordable high performance computing hardware and the introduction of user-friendly interfaces have led to the development of commercial CFD packages. Several general-purpose CFD packages have been published in past decade. Prominent among them are: PHONICS, FLUENT, SRAT-CD, CFX, FLOW -3D and COMPACT. Most of them are based on the finite volume method. Among these as mentioned FLUENT is very leading engineering software provides a state of the art computer program for modeling fluid flow and heat transfer in complex geometries. FLUENT [34] provides complete mesh flexibility, solving the flow problems with unstructured meshes that can be generated about complex geometries with relative ease. Supported mesh types include 2D triangular/ quadrilateral, 3D tetrahedral/ hexahedral/ pyramid/ wedge, and mixed (hybrid) meshes. FLUENT consists of two main parts. First part is called GAMBIT and second part is called FLUENT the solver. One can generate the required geometry and grid using GAMBIT. Also one can use T grid to generate a triangular, tetrahedral or hybrid volume mesh from the existing boundary mesh. Once mesh has been generated, it can be imports in FLUENT, all refining operations are performed within the solver. These include the setting boundary conditions, defining fluid properties, executing the solution, refining the grid viewing and post processing the results.

FLUENT provides three different solver formulations:

- segregated
- coupled implicit
- coupled explicit

The segregated and coupled approaches differ in the way that the continuity, momentum, and (where appropriate) energy and species equations are solved: the segregated solver solves these equations sequentially (i.e., segregated from one another), while the coupled solver solves them simultaneously (i.e., coupled together). Both formulations solve the equations for additional scalars (e.g., turbulence or radiation quantities) sequentially. The implicit and explicit coupled solvers differ in the way that they linearize the coupled equations.

The segregated solver traditionally has been used for incompressible and compressible flows. The coupled approach was originally designed for high-speed compressible flows. Both approaches are now applicable to a broad range of flows (from incompressible to highly compressible), but the origins of the coupled formulation may give it a performance advantage over the segregated solver for high-speed compressible flows.

By default, FLUENT uses the segregated solver, but for high-speed compressible flows, highly coupled flows with strong body forces (e.g., buoyancy or rotational forces), or flows being solved on very fine meshes, consider the coupled implicit solver instead. This solver couples the flow and energy equations, which often results in faster solution convergence. A trade-off involved in the use of the coupled implicit solver is that it requires more memory (1.5 to 2 times) than the segregated solver. For cases where the use of the coupled implicit solver is desirable, but machine does not have sufficient memory, and then use the segregated solver or the coupled explicit solver instead. The coupled explicit solver also couples the flow and energy equations, but it requires less memory than the coupled implicit solver. It will take longer to reach a converged solution with the coupled explicit solver than with the coupled implicit solver.

4.2 Radiation Model

FLUENT provides five radiation models which allow including radiation, with or without a participating medium in heat transfer simulations:

1. Discrete ordinates (DO) radiation model
2. Discrete transfer radiation model (DTRM)
3. P-1 radiation model
4. Rosseland radiation model
5. Surface-to-surface (S2S) radiation model

4.2.1 Discrete ordinate model (DO Model)

The discrete ordinates (DO) radiation model solves the radiative transfer equation (RTE) for a finite number of discrete solid angles, each associated with a vector direction $\hat{s}$ fixed in the global Cartesian system (x, y, z). Unlike the DTRM the DO model does not perform ray tracing. The DO model solves for as many transport equations as there are directions $\hat{s}$. The solution method is identical to that used for the fluid flow and energy equations. The implementation in FLUENT uses a conservative variant of the discrete ordinates model called the finite-volume scheme and its extension to unstructured meshes.

Advantages:-

- Solution method similar to that for the other conservation equations.
- Conservative method leads to heat balance for coarse discretization.
- Accuracy can be increased by using a finer discretization.
- Accounts for scattering, semi-transparent media, specular surfaces.
- Banded-gray option for wavelength-dependent transmission.

Limitations:-

- Solving a problem with a large number of ordinates is CPU-intensive.

4.2.2 Discrete transfer radiation model (DTRM)

The main assumption of the DTRM is that the radiation leaving the surface element in a certain range of solid angles can be approximated by a single ray.

Uses ray-tracing technique to integrate radiant intensity along each ray:

$$\frac{dI}{ds} = -\kappa I + \kappa I_b$$

The ray tracing technique used in the DTRM can provide a prediction of radiative heat transfer between surfaces without explicit view-factor calculations.

Advantages:-

- Relatively simple model.
- Can increase accuracy by increasing number of rays.
- Applies to wide range of optical thicknesses.

Limitations:-

- Assumes all surfaces are diffuse (isotropic reflection).
- Effect of scattering not included.
- Solving a problem with a large number of rays is CPU-intensive.

4.2.3 P1-Model

The P-1 radiation model is the simplest case of the more general P-N model, which is based on the expansion of the radiation intensity I into an orthogonal series of spherical harmonics.

Advantages:-

- Radiative transfer equation easy to solve with little CPU demand.
- Includes the effect of scattering.
- Works reasonably well for combustion applications where optical thickness, is large.
- Easily applied to complicated geometries with curvilinear coordinates.
- Effects of particles, droplets, and soot can be included.

Limitations:-

- Assumes all surfaces are diffuse.
- There may be a loss of accuracy, depending on complexity of geometry, if optical thickness is small.
- Tends to over predict radiative fluxes from localized heat sources or sinks.

4.2.4. Rosseland Model

The Rosseland or diffusion approximation for radiation is valid when the medium is optically thick, and is recommended for use in problems where the optical thickness is greater than 3. It can be derived from the P-1 model equations, with some approximations.

Advantages:-

- It does not solve an extra transport equation for the incident radiation (as the P-1 model does).
- The Rosseland model is faster than the P-1 model and requires less memory

Limitations:-

- The Rosseland model can only be used for optically thick media. It is recommended for use when the optical thickness exceeds 3.
- The Rosseland model is not available when one of the coupled solvers is being used; it is available only with the segregated solver.

4.2.5. Surface-to-Surface (S2S) Radiation Model

The surface-to-surface radiation model can be used to account for the radiation exchange in an enclosure of gray-diffuse surfaces. The energy exchange between two surfaces depends in part on their size, separation distance, and orientation. These parameters are accounted for by a geometric function called a view factor. The main assumption of the S2S model is that any absorption, emission, or scattering of radiation can be ignored; therefore, only surface-to-surface" radiation need be considered for analysis. The surface-to-surface radiation model is good for modelling the enclosure radiative transfer without participating media (e.g., spacecraft heat rejection system, solar collector systems, and radiative space heaters).

Advantages:-

- The S2S model has a much faster time per iteration as compared to DTRM and DO radiation model.

Limitations:-

- The S2S model assumes that all surfaces are diffuse.
- The implementation assumes gray radiation.
- The S2S model cannot be used to model participating radiation problems.
- The surface clustering method does not work with sliding meshes or hanging nodes.
- The S2S model cannot be used if your model contains periodic or symmetry boundary conditions.
- The S2S model cannot be used with 2d axisymmetric geometries.
- The S2S model cannot be used for models with multiple enclosures. Only single enclosure geometries can be treated using the S2S model.

4.2.6 Choosing a Radiation Model

The following method is used to decide which radiation model to use for certain problems

- **Optical thickness:** The optical thickness is a good indicator of which model to use in problem. If $\tau >> 1$, best alternatives are the P-1 and Rosseland models. The P-1 model should typically be used for optical thicknesses > 1. For optical thickness > 3, the Rosseland model is cheaper and more efficient. The DTRM and the DO model work across the range of optical thicknesses.
- **Scattering and emissivity:** The P-1, Rosseland, and DO models account for scattering, while the DTRM neglects it. Since the Rosseland model uses a temperature slip condition at walls, it is insensitive to wall emissivity.

- **Particulate effects:** Only the P-1 and DO models account for exchange of radiation between gas and particulates.
- **Semi-transparent media and specular boundaries:** Only the DO model allows specular reflection (e.g., for mirrors) and calculation of radiation in semi-transparent media such as glass.
- **Non-gray radiation:** Only the DO model allows you to compute non-gray radiation using a gray band model.
- **Localized heat sources:** In problems with localized sources of heat, the P-1 model may over predict the radiative fluxes. The DO model is probably the best suited for computing radiation for this case, although the DTRM, with a sufficiently large number of rays, is also acceptable.
- **Enclosure radiative transfer with non-participating media:** The surface-to-surface (S2S) model is suitable for this type of problem.

DOM is the only model that works across the full range of conditions.

4.3 Problem Solving Steps

After determining the important features of the problem following procedural steps are followed for solving it

1. Create the model geometry and grid.

2. Start the appropriate solver for 2D or 3D modelling.

3. Import the mesh.

4. Check the grid.

5. Select the solver formulation.

6. Choose the basic equations to be solved: energy equation, radiation model etc.

7. Specify material properties.

8. Specify the boundary conditions.

9. Adjust the solution control parameters.

10. Initialize the flow field.

11. Iterate.

12. Examine the results.

13. Save the results.

14. If necessary, refine the grid or consider revisions to the numerical or physical model.

Chapter 5

Results and Discussion

- **Introduction**
- **Isotropic scattering**
- **Linear Anisotropic scattering & Rayleigh scattering**

5.1 Introduction

In this chapter, the whole work is divided into two parts, first isotropic scattering and second linear anisotropic scattering & Rayleigh scattering. It is assume that the radiation is the only modes of energy transfer and the system is in steady state. The diffuse gray surface and homogenous medium is considered. The isotropic scattering section are contains five cases

1. isothermal absorbing emitting medium
2. purely scattering medium
3. three-dimensional enclosure filled with absorbing-emitting medium
4. collimated incidence
5. non-isothermal gray participating medium

The linear anisotropic scattering and Rayleigh scattering section contains one case

1. scattering gray planar medium

5.2 Isotropic scattering

Isotropic scattering scatters energy equally into all directions. The anisotropic factor is zero, the scattering is known as isotropic scattering. For isotropic scattering, scattering phase function Φ=1.

5.2.1 Isothermal absorbing emitting medium

In isothermal absorbing emitting medium, the medium only absorbs and emits, the scattering coefficient of the medium is zero. The side of the square is taken as L_x=L_y=1 m as shown in Fig. 3.2. The medium is maintained at a constant temperature T_g =300K. The all walls of square enclosure maintained at cold walls at 0 Kelvin. All the walls of the enclosure are black.

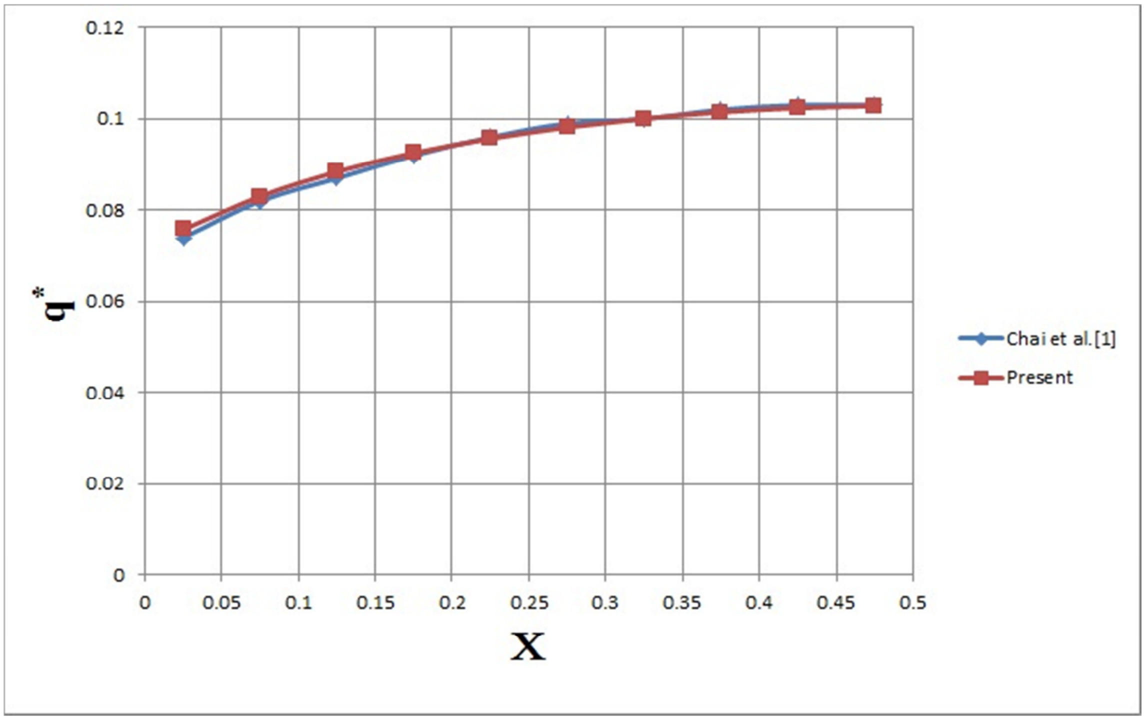
The calculation domain is discretized into 20×20 uniform control volumes in the X and Y directions. Angular discretization is used that of 1×8 control angles with uniform $\Delta\theta$ and $\Delta\varphi$ in the θ and φ directions respectively.

The dimensionless heat flux on the bottom wall is

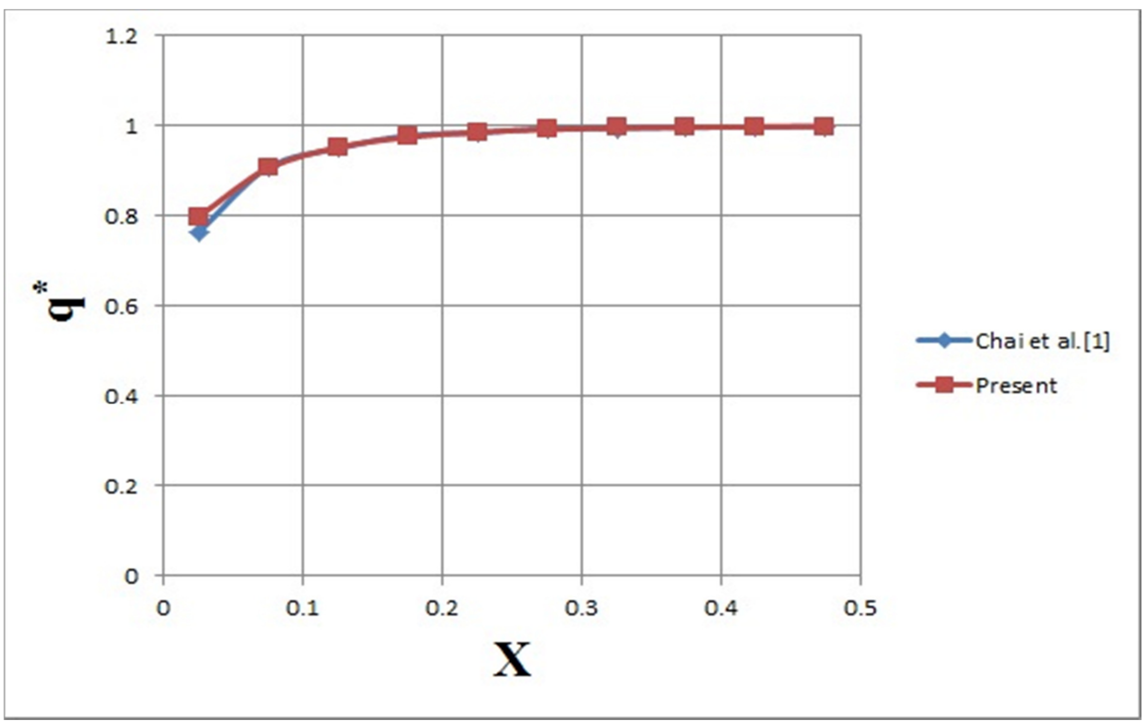
$$q^* = q/\sigma T_g^4.$$

The effects of absorption coefficient are shown in Fig. 5.1 and 5.2 on dimensionless heat flux and radiation temperature respectively. In Fig. 5.1(a) and (b), the dimensionless heat flux along the bottom wall is plotted for absorption coefficient 0.1 and 10 m^{-1} respectively. The value of absorption coefficient is constant and it does not depend on temperature. Only one half of the domain is shown for symmetry reasons. The present result is compared with the result of Chai and found that both the graph are overlapping.In Fig. 5.2(a), (b) and (c), the contours of radiation temperature are plotted for absorption coefficient 0.1,1 and 10 m^{-1} respectively. From Table 5.1 when the absorption coefficient is increases, radiation heat flux rate transferred through the walls is increases and walls absorb the energy. The energy absorbed by the wall is converted into internal energy. That's why the dimensionless heat flux and radiation temperature are increases with absorption coefficient. The negative sign of heat transfer rate indicates that the heat transferred to outside the domain.

A grid independent test was done with different spatial and angular grid size. It is observed that further refinement to the grid size of 40× 40 control volume and 4× 8 control angles results in negligible change in the results as seen in Fig 5.3 and Fig 5.4.



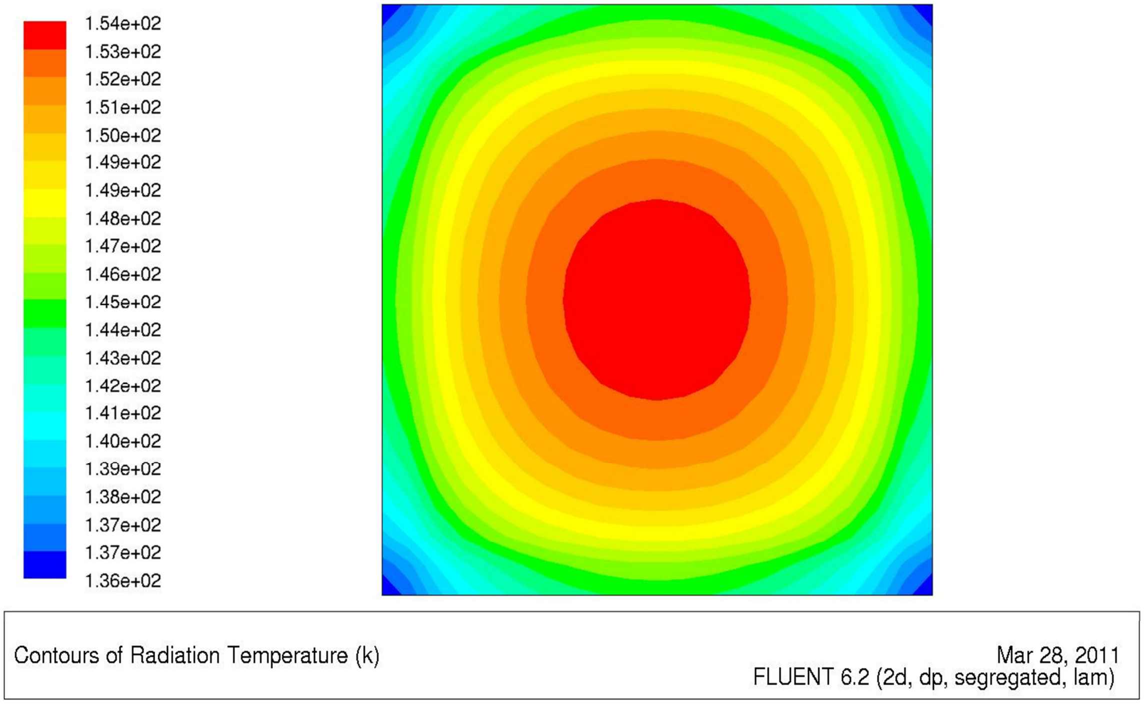
(a)



(b)

Figure 5.1 Dimensionless heat flux along the bottom wall for absorption coefficient (a) κ=0.1m^{-1}

(b) κ =10 m^{-1}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1.53e+02
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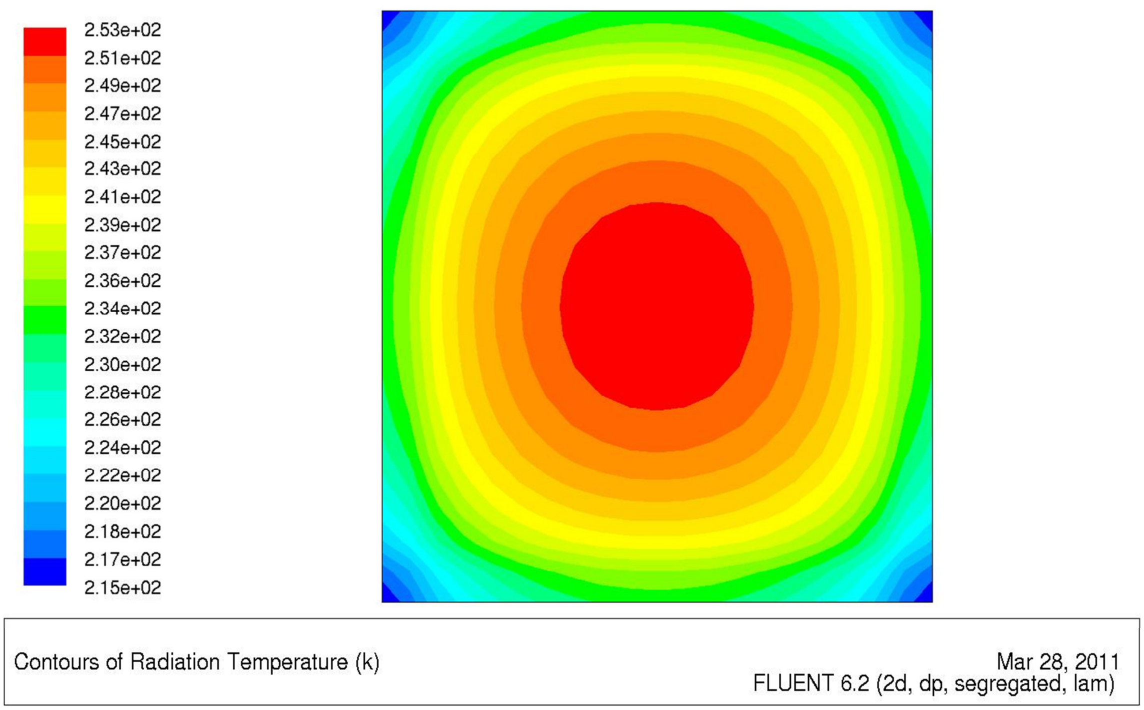
1.47e+02
1.46e+02
1.45e+02
1.44e+02
1.43e+02
1.42e+02
1.41e+02
1.40e+02
1.39e+02
1.38e+02
1.37e+02
1.37e+02
1.36e+02
Contours of Radiation Temperature (k)
Mar 28, 2011
FLUENT 6.2 (2d, dp, segregated, lam)

(a)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2.37e+02
2.36e+02
2.34e+02
2.32e+02
2.30e+02
2.28e+02
2.26e+02
2.24e+02
2.22e+02
2.20e+02
2.18e+02
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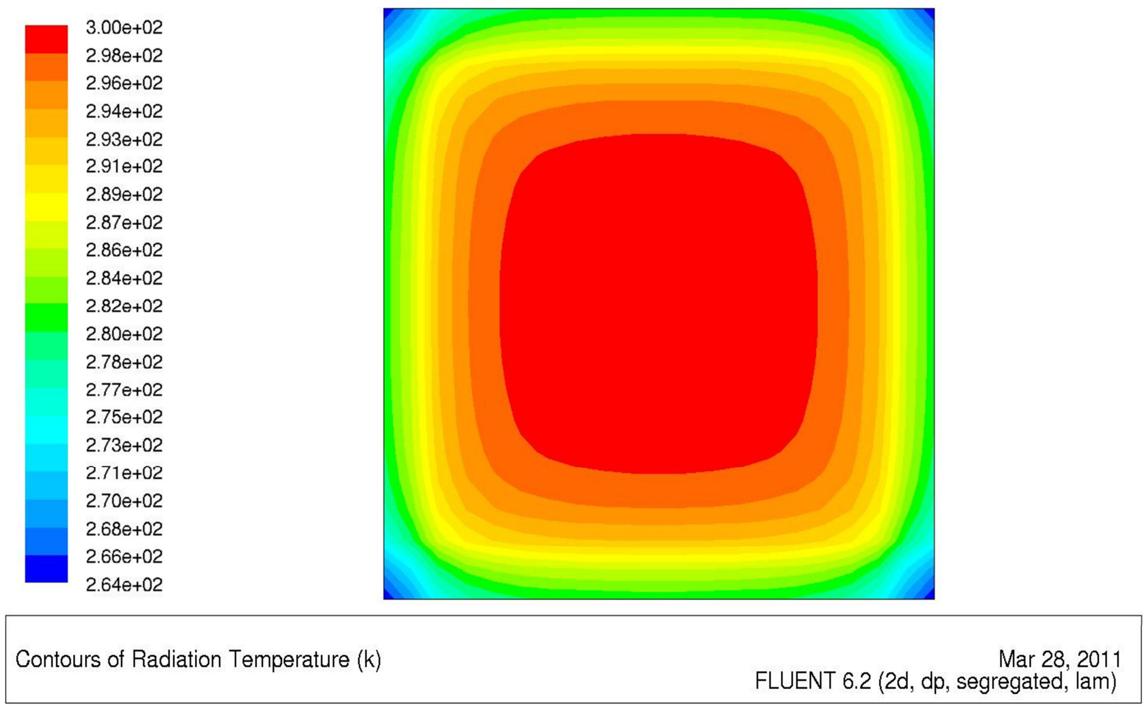
2.15e+02
Contours of Radiation Temperature (k)
Mar 28, 2011
FLUENT 6.2 (2d, dp, segregated, lam)

(b)



(c)

Figure5.2. contours of radiation temperature for absorption coefficient (a) κ=0.1 m^{-1}(b) κ=1m^{-1}

(c) κ=10 m^{-1}

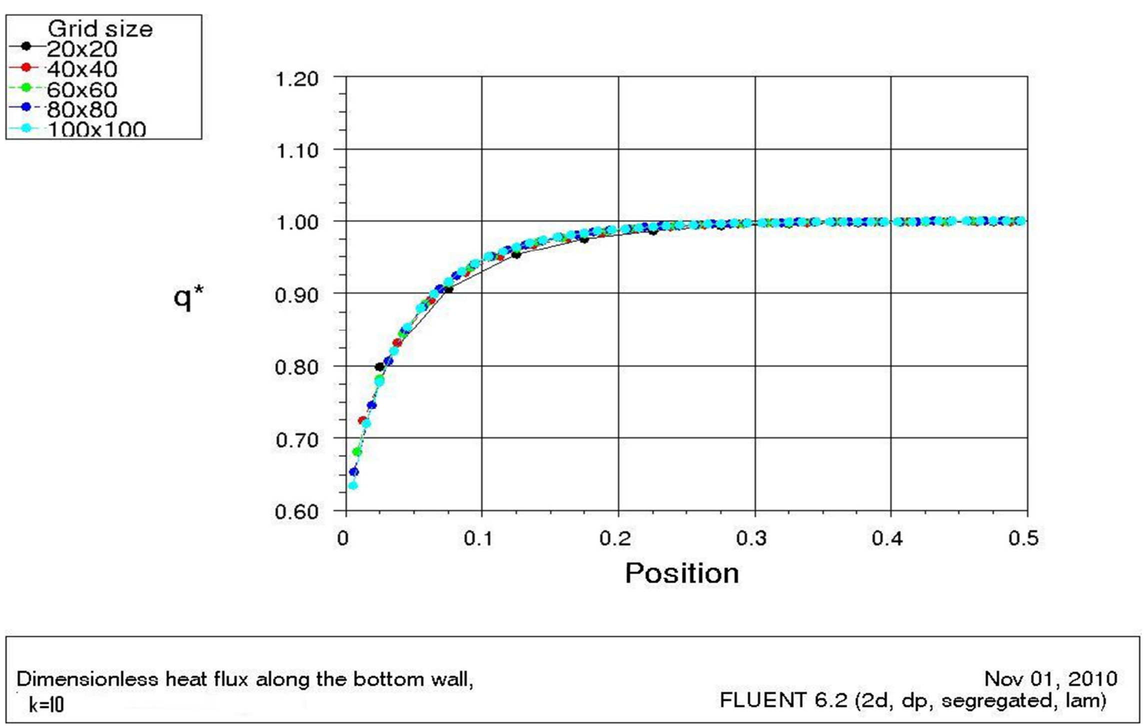


Figure 5.3 Grid independent tests for grid size

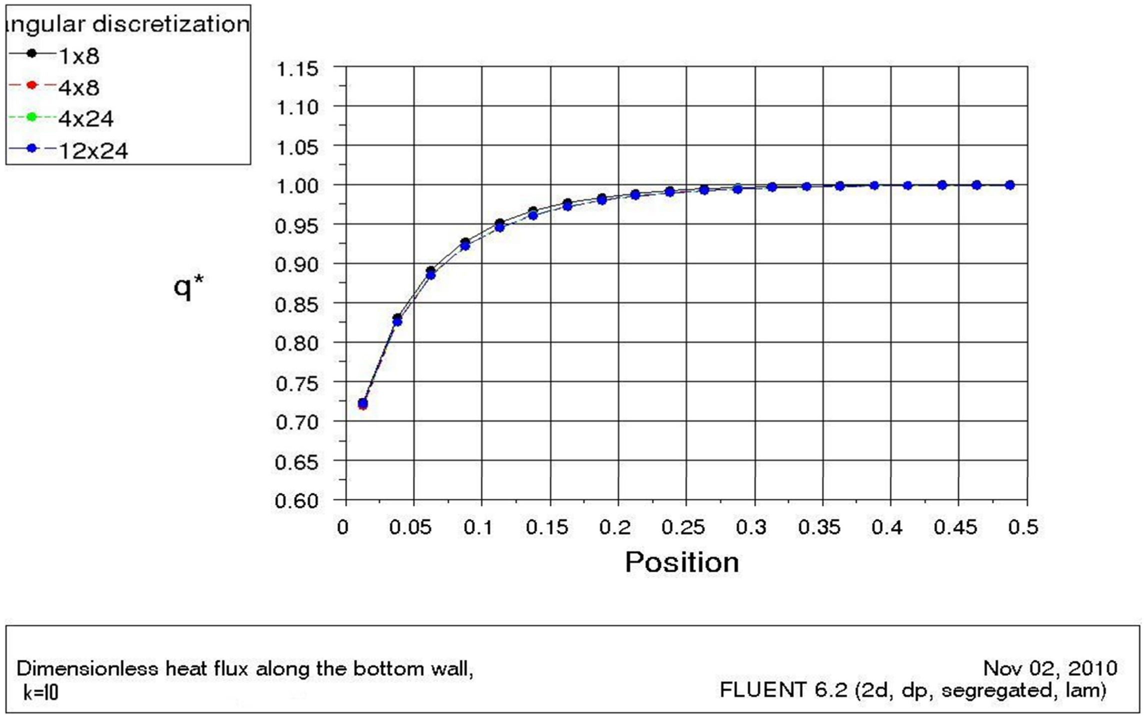


Figure 5.4 Grid independent tests for angular discretization

Table 5.1 Radiation heat transfer rate for various absorption coefficients

Absorption coefficient(m^{-1})	Radiation heat transfer rate (Watt)	
	Bottom wall	**Top wall**
κ=0.1	-43.187895	-43.187895
κ=10	-441.06987	-441.06987

5.2.2 Purely scattering medium

In purely scattering medium, the medium scatters radiation, but does not absorb or emits. A square enclosure shown in Fig. 5.5 is considered with black walls and the medium scatters energy isotropically with the scattering coefficient as unity. The side of the square is taken as L_x=L_y=1 m. The bottom wall is hot maintained at a temperature T_h=300K with the remaining walls maintained at 0 Kelvin. The two different grid size and angular discretization are considered (i) (9×9) and (2×12) (ii) (31×31) and (5×24).

The dimensionless heat flux on the bottom wall for square enclosure is

$$q^{***} = q/\sigma(T_h^4 - T_c^4)$$

The dimensionless heat flux is plotted on the ordinate and position along the X-direction is plotted on abscissa. Only one half of the domain is shown for symmetry reasons. The dimensionless heat flux on the bottom wall are plotted in Fig. 5.6 .When coarse grid is used, FLUENT overpredicts the heat flux, but it approaches the exact solution with grid refinement. The dimensionless heat flux for varying emissivity on the top wall is shown in Fig 5.7. The dimensionless heat flux maximum for black wall, when the emissivity is decreases the heat flux also decreases.

The geometries of rectangular enclosure created with aspect ratio L_y/L_x=10.The grid size is 31×61 and angular discretization is 5×24.

The dimensionless centerline incident radiation for rectangular enclosure is

$$G^* = G/ (4\sigma T_b^4)$$

The incident radiation is calculated at x=0.5 m. The dimensionless incident radiation is plotted on ordinate and position along the Y-direction on abscissa as shown in Fig. 5.8

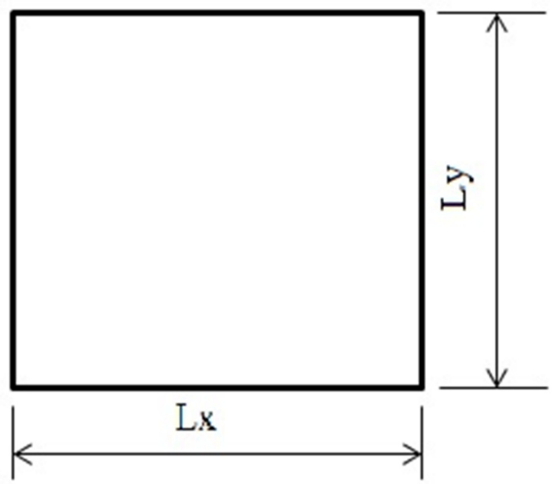
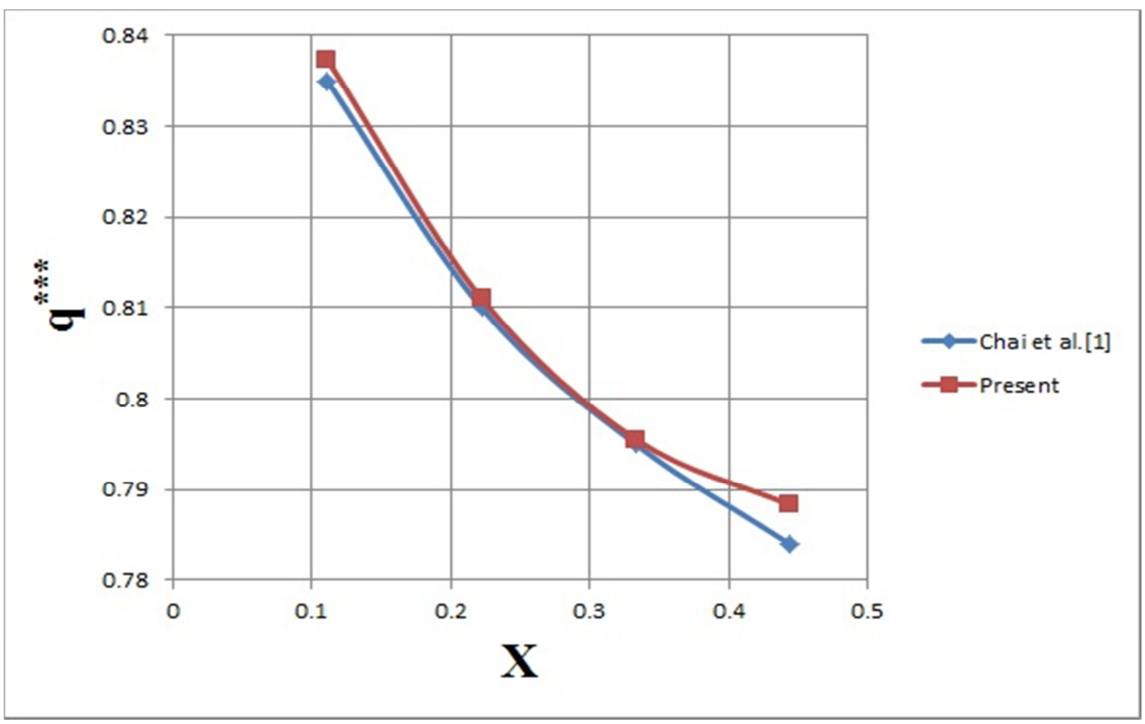
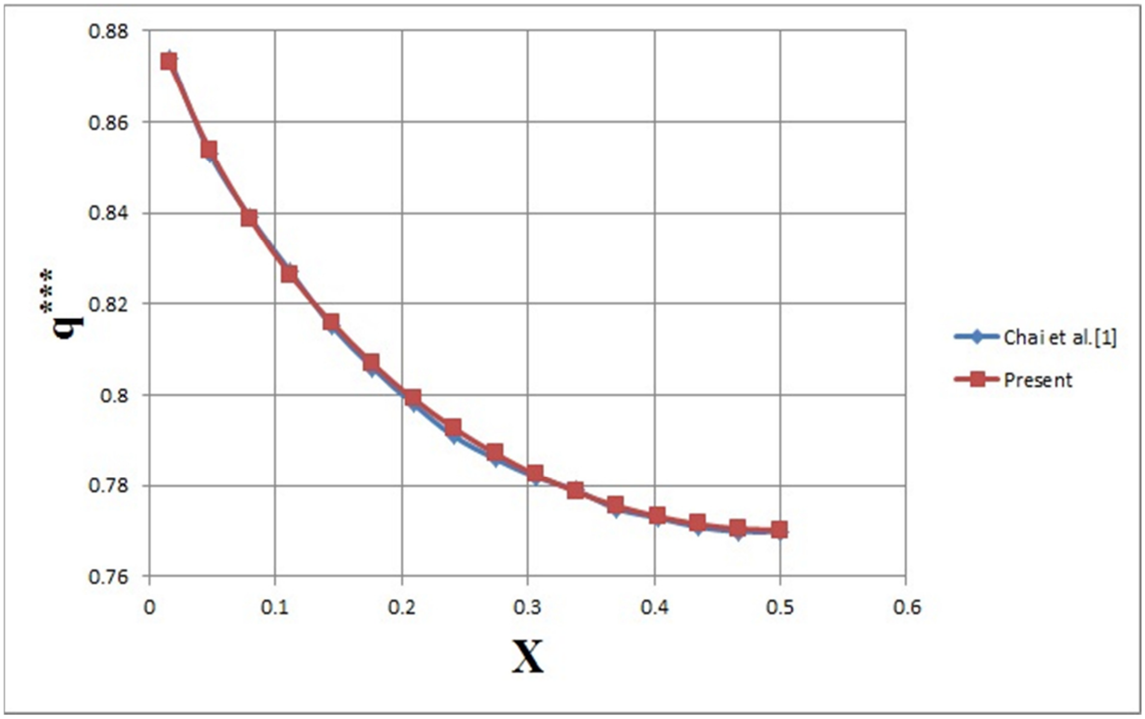


Figure 5.5 square enclosure L_y/L_x=1



(a)



(b)

Fig. 5.6 Dimensionless heat flux for grid size and angular discretization (a)9×9 and 2×12 (b)31×31 and 5×24

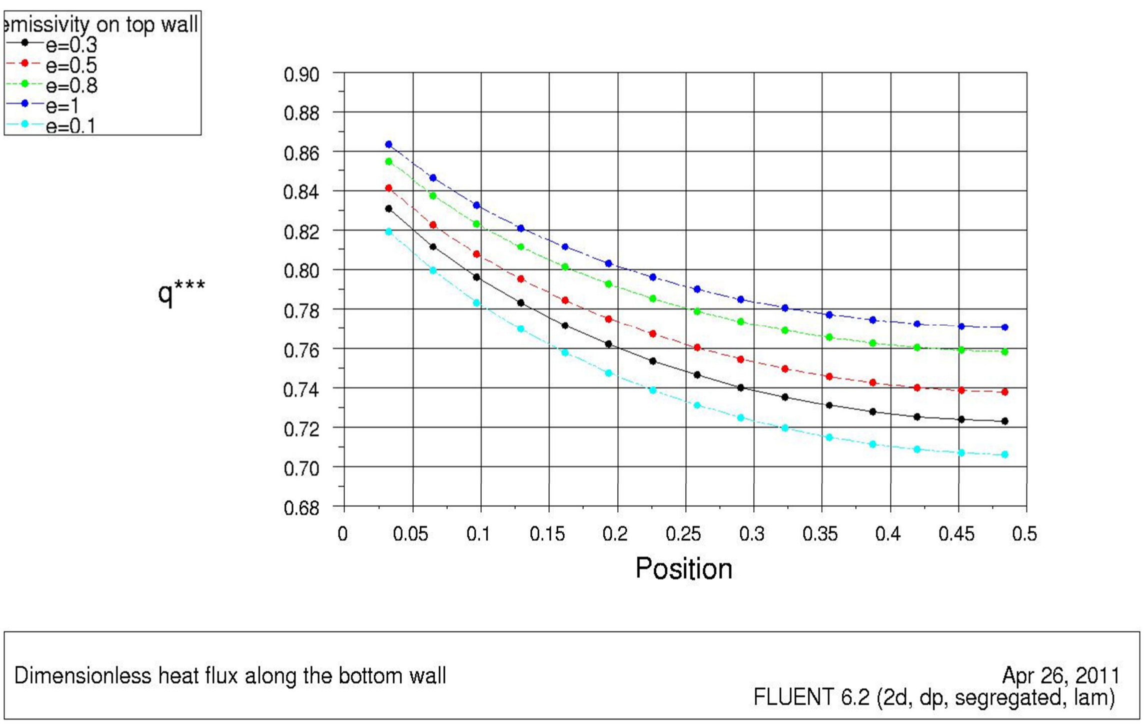


Figure5.7 Dimensionless heat flux for varying emissivity on top wall

Table 5.2 Radiation heat transfer rate for various emissivity on top wall

Emissivity	Radiation heat transfer rate(Watt)	
	Bottom wall	Top wall
ε=0.1	342.35686	-12.63254
ε=0.3	349.08332	-36.11416
ε=0.5	355.20378	-57.48518
ε=0.7	363.40959	-86.176026
ε=1	368.32135	-103.38164

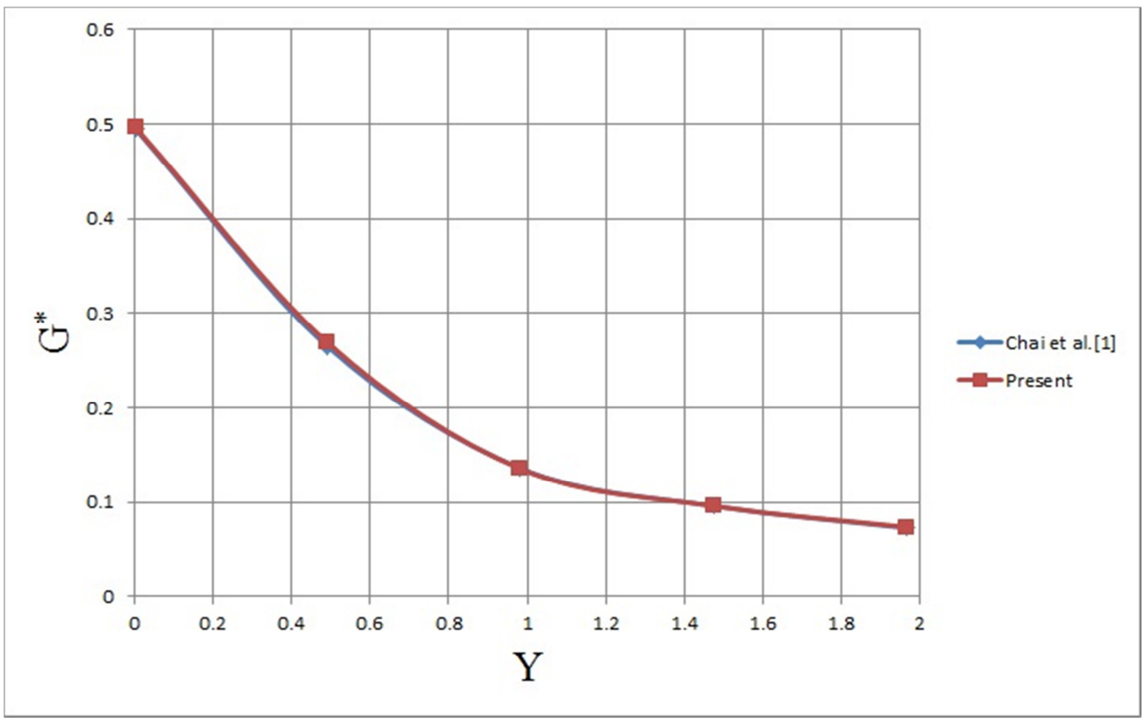


Figure 5.8 Dimensionless incident radiation for rectangular enclosure L_y/L_x=10

5.2.3 Three-dimensional enclosure filled with absorbing-emitting medium

The 3-dimensional enclosure filled with an absorbing-emitting medium with κ=0.5 m^{-1}.The size of three-dimensional enclosure is 2×2×4 m. The 3-D enclosure is divided into 25× 25× 25 control volumes shown in Fig.5.9.The angular discretization in θ and φ direction is 4×20.

The temperature distribution is determined from the RTE is coupled with the energy equation with a heat source of q_{gen}=5 kw/m^3.

$$\nabla . q = q_{gen} = \kappa(4\pi I_b - G)$$

The boundary conditions are

z=0, T=1200K, $\varepsilon = 0.85$

z=4m, T=400K, $\varepsilon = 0.70$

Others, T=900K, $\varepsilon = 0.70$

The Result obtained with the help of FLUENT is compared with Chai's result as shown in Fig. 5.10.The static temperature is determined at z=0.4, 2, 3.6 and y=1m.The static temperature is plotted on the ordinate and position along the X-direction plotted on the abscissa as shown in Fig.5.11.The contours of radiation temperature at x= 1m for absorption coefficient 0.25, 0.5 and 1 as shown in Fig. 5.12(a), (b) and (c) respectively. When the absorption coefficient is decreases from 1 to 0.25, the temperature at z=4 m is increases. This is due to when the absorption coefficient is less, the energy absorbed by the medium is less than the more heat flux is reached to the wall (z=4m).

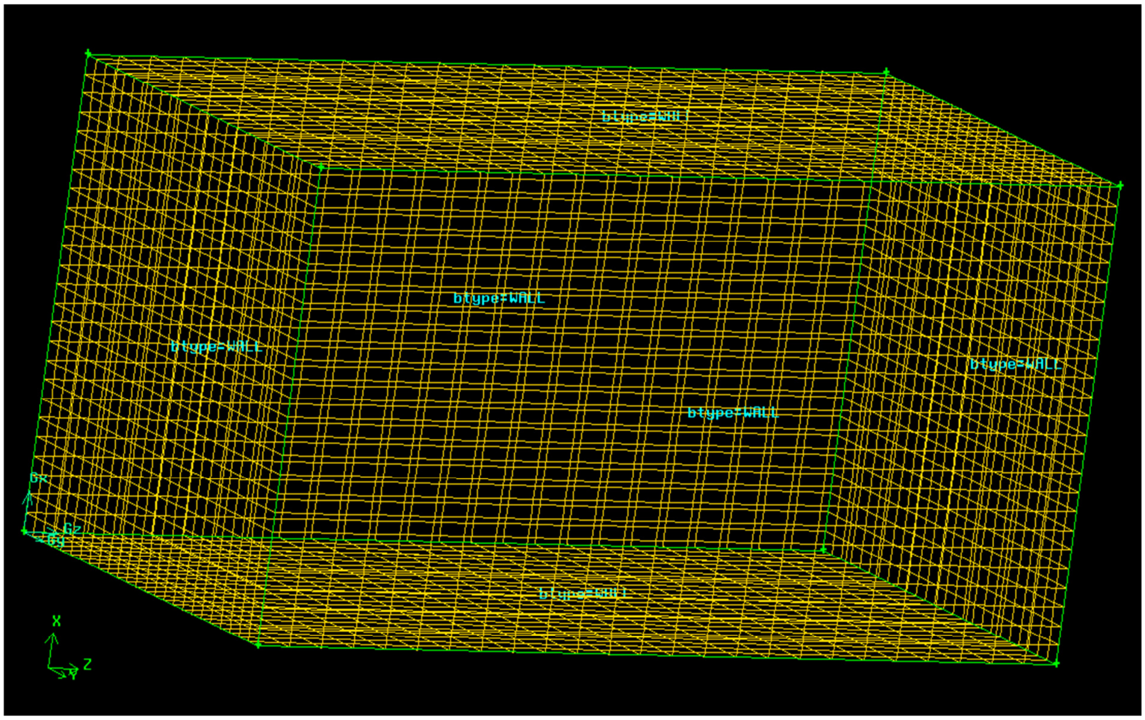


Figure 5.9 3-D enclosures of grid size 25 ×25 ×25

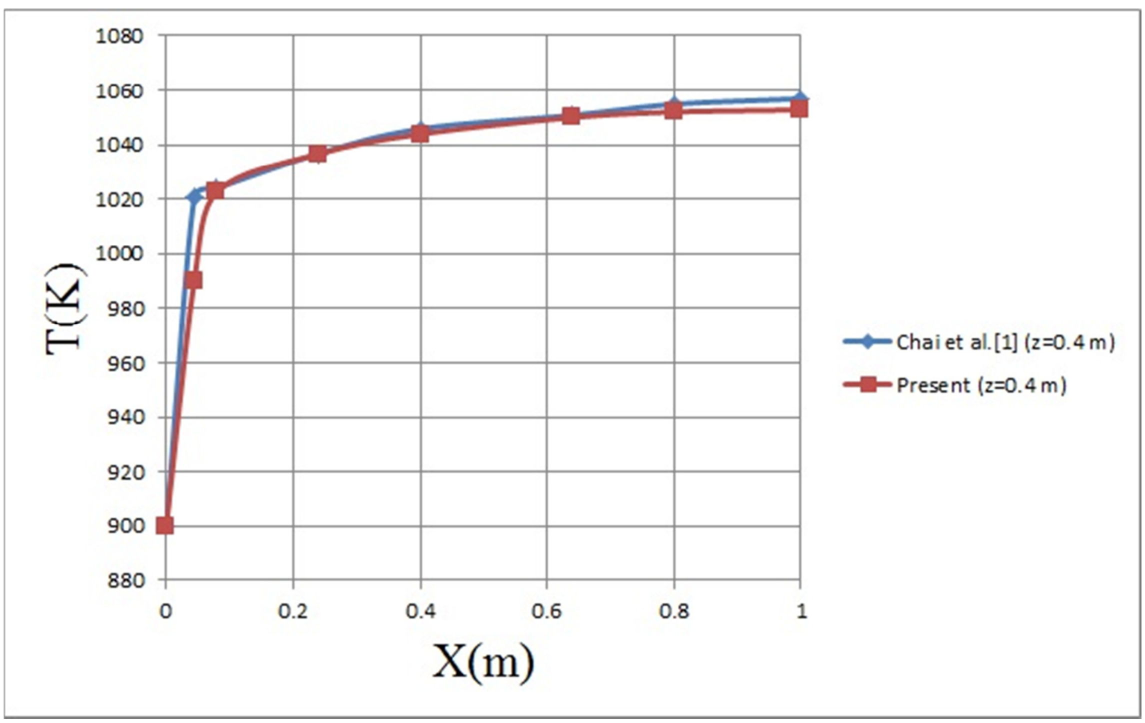
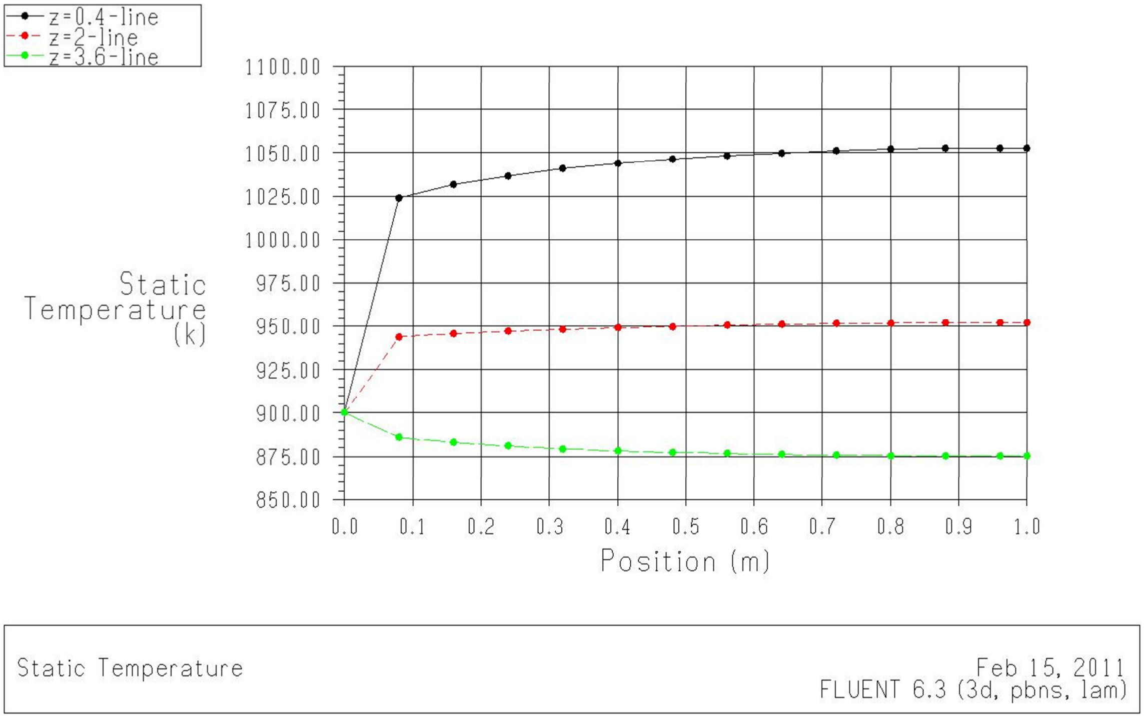
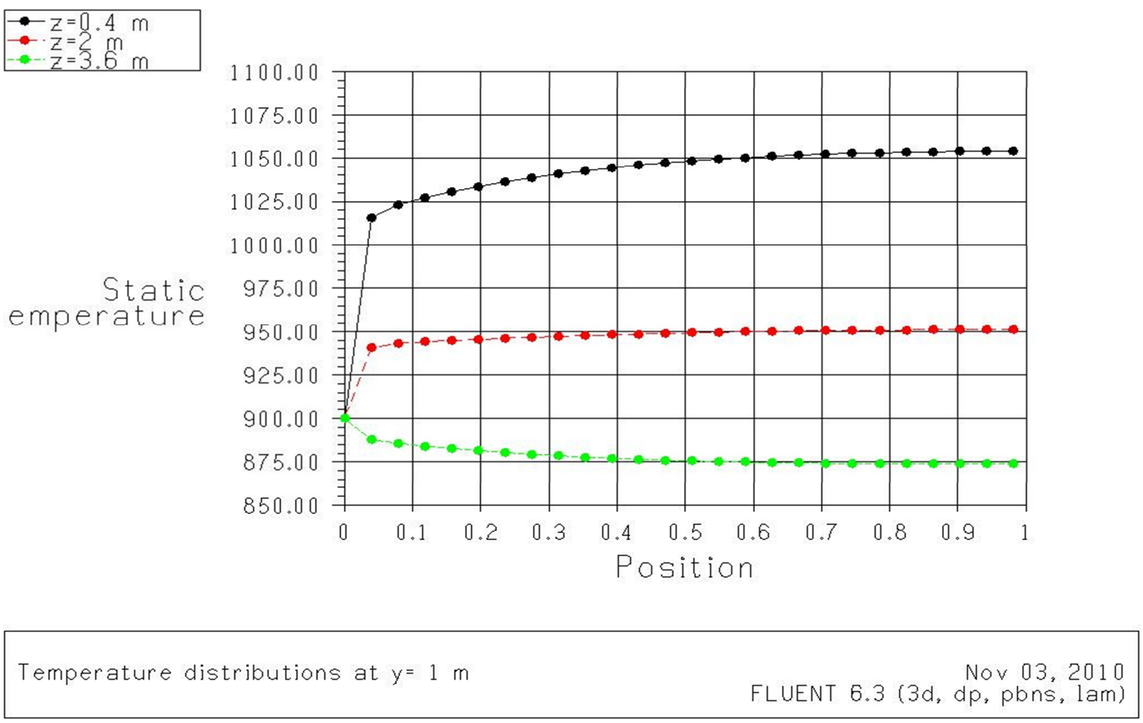


Figure 5.10 Temperature distribution at y=1m and z=0.4 m

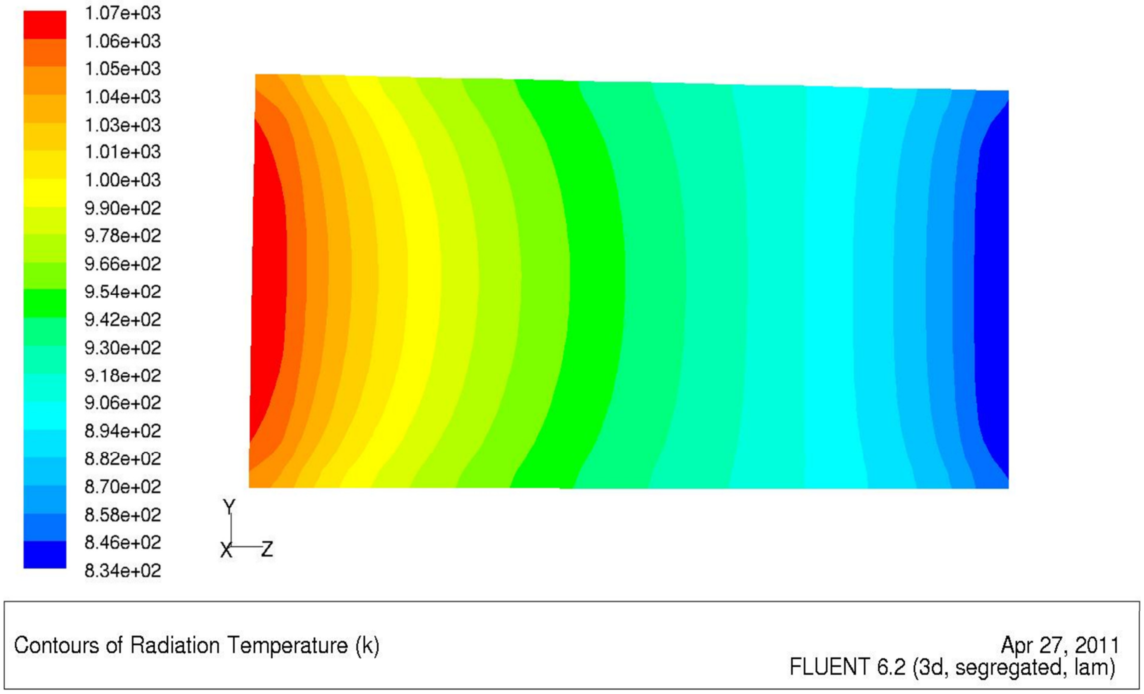


(a)



(b)

Figure 5.11 Temperature distribution at y=1 m for grid size(a)25×25×25(b) 50 × 50 × 50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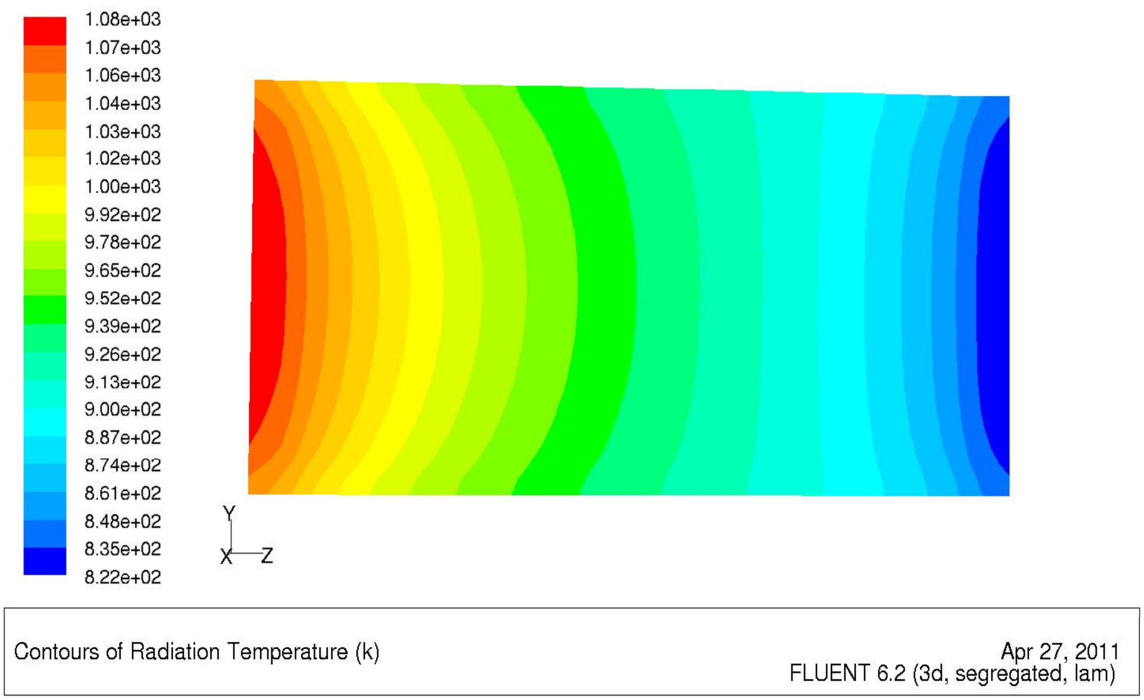
9.78e+02
9.66e+02
9.54e+02
9.42e+02
9.30e+02
9.18e+02
9.06e+02
8.94e+02
8.82e+02
8.70e+02
8.58e+02
8.46e+02
8.34e+02
Y
X
Z
Contours of Radiation Temperature (k)
Apr 27, 2011
FLUENT 6.2 (3d, segregated, lam)

(a)


1.08e+03
1.07e+03
1.06e+03
1.04e+03
1.03e+03
1.02e+03
1.00e+03
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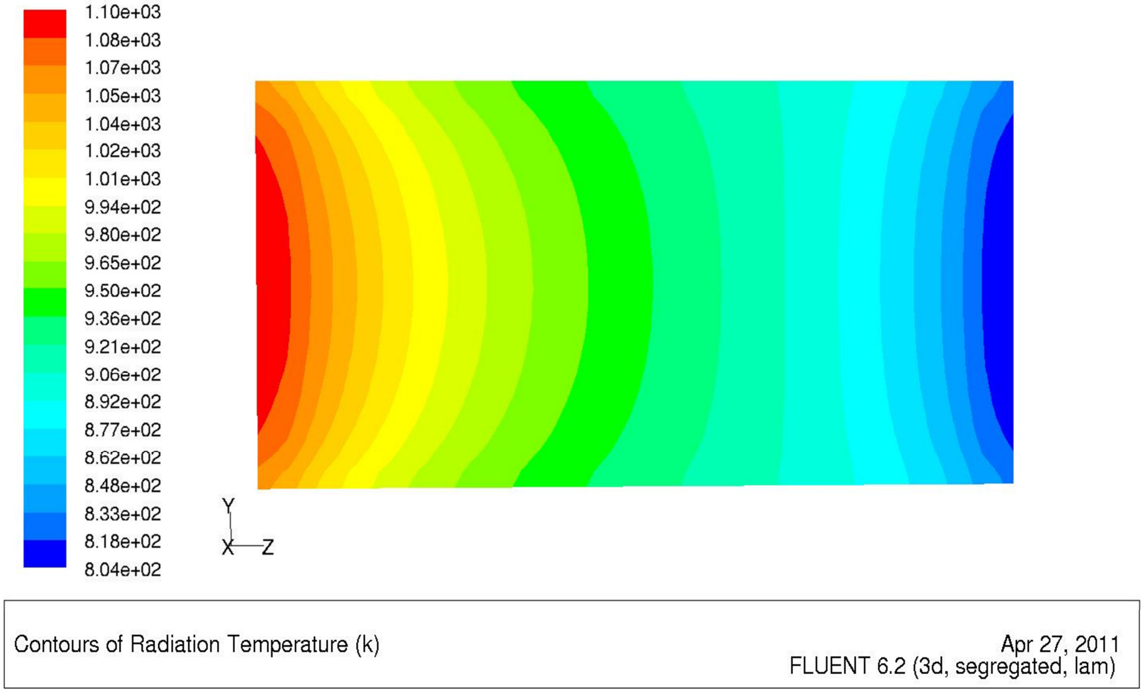
9.78e+02
9.65e+02
9.52e+02
9.39e+02
9.26e+02
9.13e+02
9.00e+02
8.87e+02
8.74e+02
8.61e+02
8.48e+02
8.35e+02
8.22e+02
Y
X
Z
Contours of Radiation Temperature (k)
Apr 27, 2011
FLUENT 6.2 (3d, segregated, lam)

(b)



(c)

Figure5.12 contours of radiation temperature at x=1m for absorption coefficient (a) κ=0.25 m^{-1} (b) κ=0.5 m^{-1} (c) κ =1m^{-1}

5.2.4 Collimated incidence

Collimated beam is a beam of radiation or matter whose rays or particles are nearly parallel so that the beam does not converge or diverge appreciably.The top wall of square enclosure is subjected to a normal collimated incidence as shown in Fig.5.13. The other walls are maintained at 0 Kelvin and the medium scatters energy isotropically with a scattering albedo of unity. All the walls of the enclosures are black. The domain is divided into 25 × 25 control volumes and 3 × 24 control angles in the θ and φ directions.

Transmittance is defined as the net dimensionless radiative heat flux emerging out of the medium at bottom wall; Reflectance is the net radiative flux from the top wall as shown in Fig. 5.14.Transmittance at bottom wall and reflectance from top wall as shown in Fig.5.15. Fig5.16 shows the effect of angle of incidence on reflected flux from the top wall. Fig. 5.17 shows the effect of angle of incidence on transmitted flux at bottom wall. Reflected flux from the top wall and transmitted flux at bottom wall maximum when the top wall is subjected to normal collimated beam.

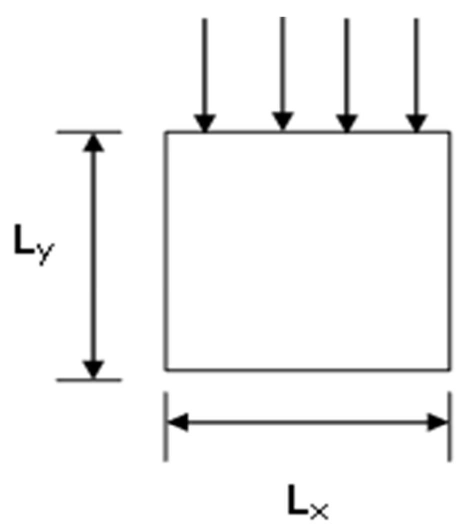


Figure 5.13 Square Enclosure with collimated radiation

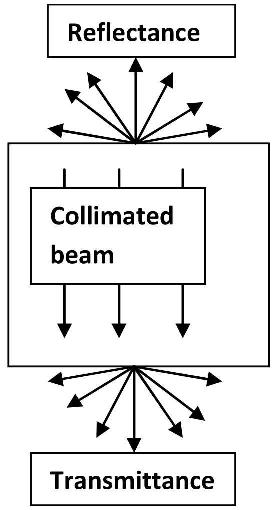


Figure 5.14 Reflectance & Transmittance for an enclosure with collimated radiation

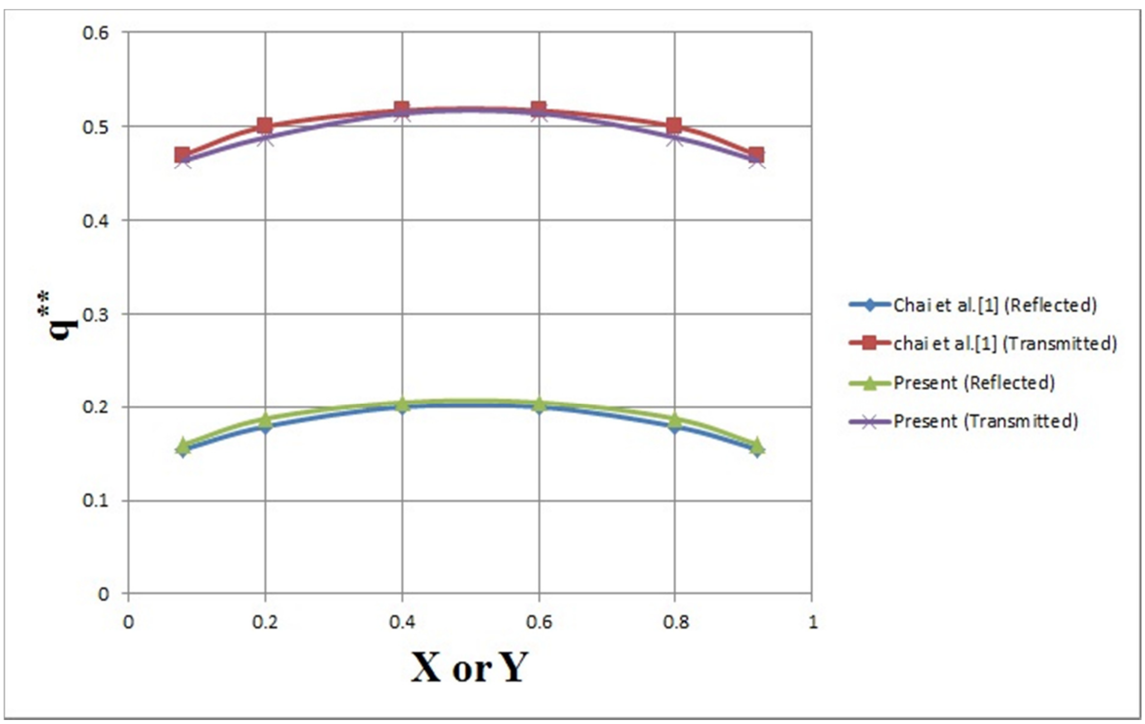


Figure 5.15 Transmittance (Bottom wall) & Reflectance (Top wall)

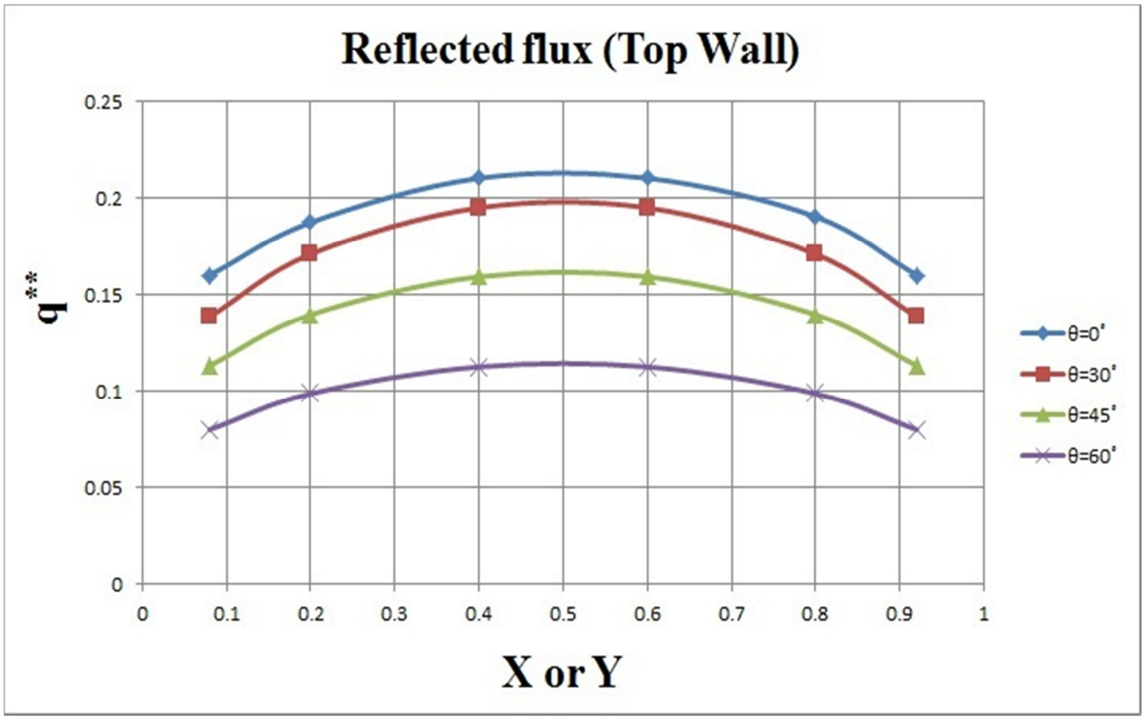


Figure 5.16 Reflected flux on top wall for different angle of incidence

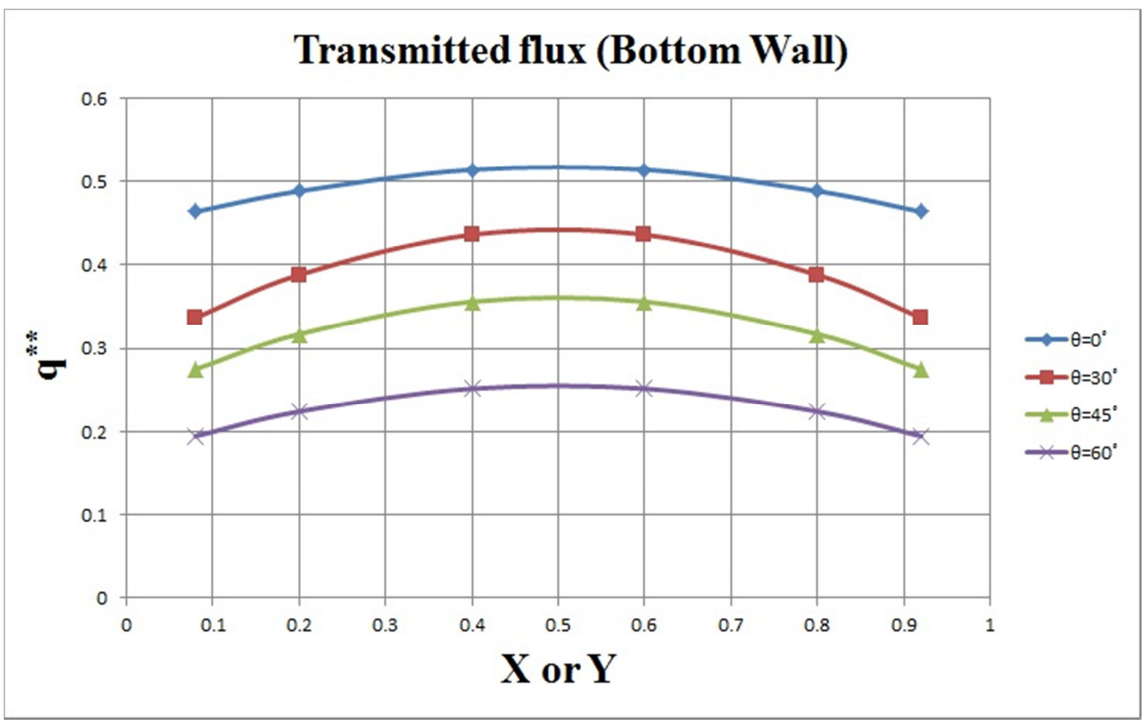


Figure 5.17 Transmitted flux on bottom wall for different angle of incidence

5.2.5 Non-isothermal gray participating medium

Consider an absorbing, emitting, isotropically scattering, non-isothermal gray medium bounded by parallel walls, gap between them is 1m and infinite length in X-direction as shown in Fig. 5.18. The domain is divided into 1000 × 10 control volumes and 4 × 20 control angles in the θ and φ directions. The top wall is maintained at temperature T_2=400K and ε_2=0.8.The bottom wall is maintained at temperature T_1=800K and ε_1=0.2.

Temperature inside the medium for absorption coefficient $\kappa=1m^{-1}$ is compared with Spiga's result as shown in Fig 5.19. It shows that result obtained using FLUENT is in good agreement with the Spiga's solution. Fig 5.20 shows the effect of the absorption coefficient on radiation temperature. The radiation temperature becomes steeper as the absorption coefficient increases, while the temperature slips at the boundaries decrease. When the absorption coefficient $\kappa=0.001m^{-1}$, then the medium is nonparticipating and no heat flux is absorbed by the medium. The medium is approximately isothermal. But when the absorption coefficient is increases, radiation temperature is also increase.Fig.5.21 shows the effect of emissivity on radiation temperature. The emissivity on the bottom wall is increases the radiation temperature also increases. Because the emissivity on the wall is decreases, reflectivity is also increases. Fig 5.22 shows the effect of bottom wall temperature on radiation temperature. The temperature slip on both boundaries increases with bottom wall temperature.

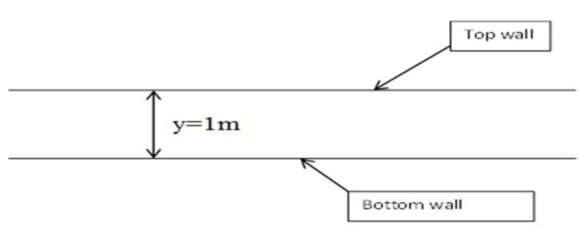


Figure 5.18 Two parallel wall between 1 m gaps

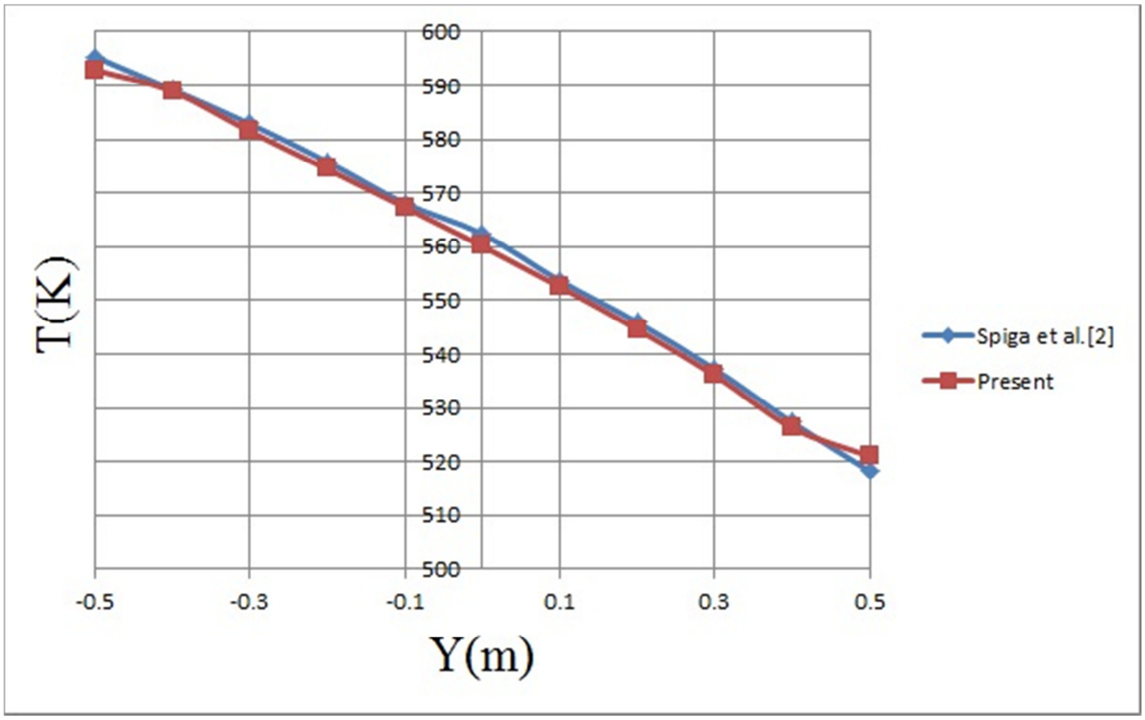


Figure 5.19 Comparison of temperature inside medium for absorption coefficient κ=1m^{-1}

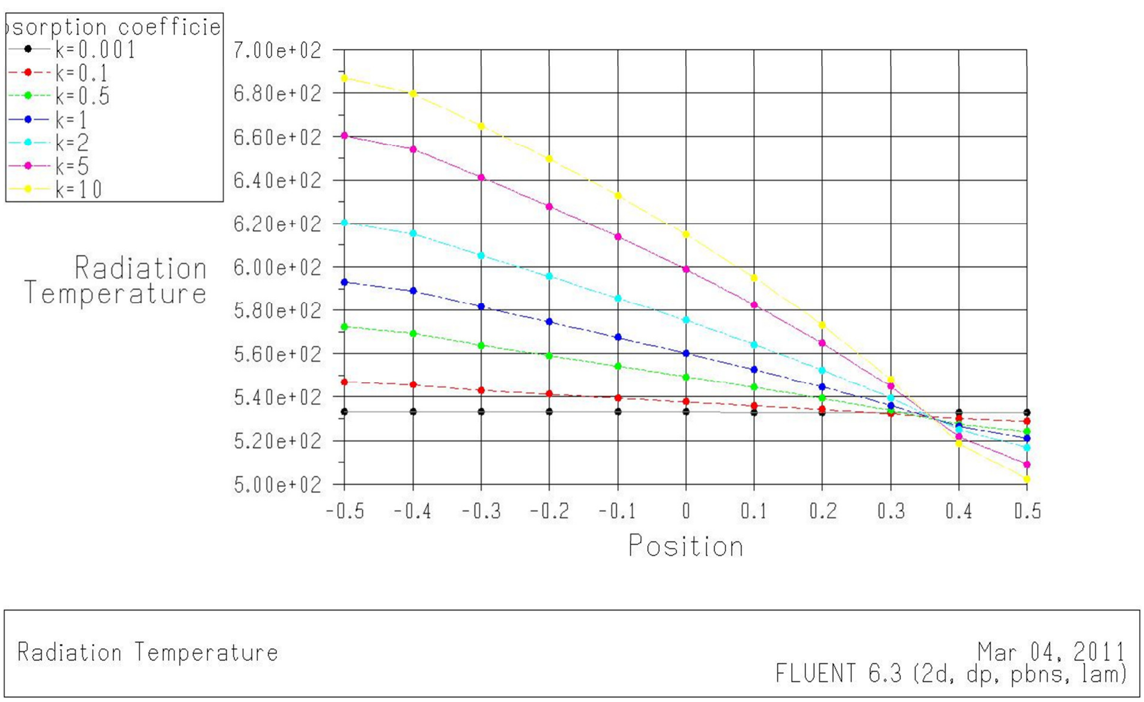


Figure 5.20 Radiation temperatures for varying absorption coefficient

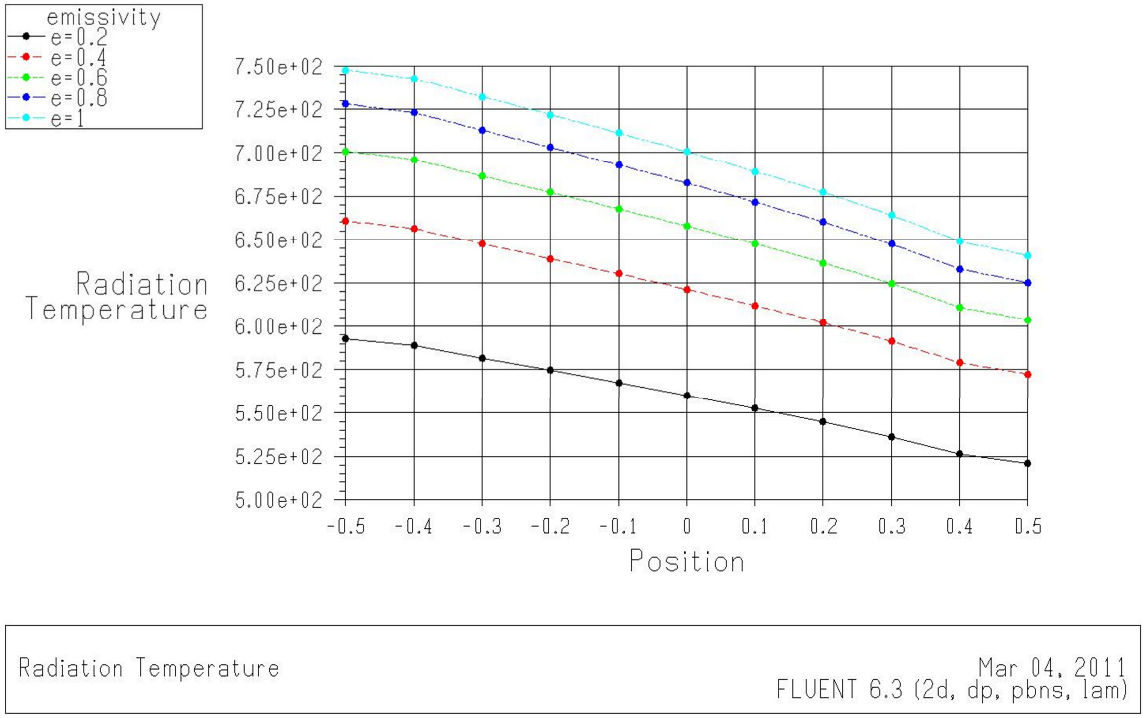


Figure 5.21 Radiation temperatures for varying emissivity on the bottom wall

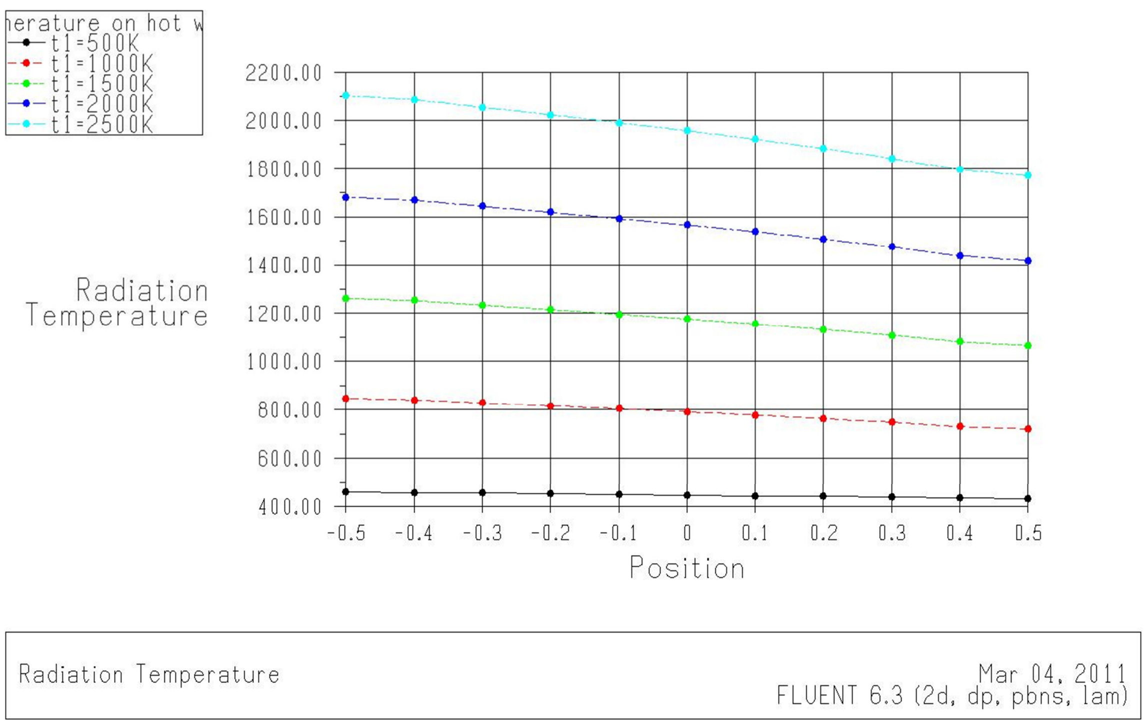


Figure 5.22 Radiation temperatures for varying bottom wall temperature

5.3 Linear anisotropic scattering & Rayleigh scattering

The linear anisotropic phase function is

$$\Phi(\hat{s}', \hat{s}) = 1 + a_1(\hat{s}'.\hat{s})$$

Where a_1 is the linear-anisotropic factor, which is a property of the fluid. Linear anisotropic factor ranges from -1to 1. A positive value indicates that more radiant energy is scattered forward than backward, and a negative value means that more radiant energy is scattered backward than forward. A zero value defines isotropic scattering.

The Rayleigh phase function is

$$\Phi(\hat{s}', \hat{s}) = 3/4(1 + (\hat{s}'.\hat{s})^2)$$

For Rayleigh scattering, the scattered energy is directed preferentially along the forward direction of the incident radiation and strongly back toward the radiation source.

5.3.1 Scattering gray planar medium

In section 5.2.1 and 5.2.2 is discuss for isotropic scattering, but here it is discuss about anisotropic scattering. This section has been discussed about two cases; first case is the absorbing, emitting, and scattering medium and second case the scattering medium.

A user defined function (UDF), is program that can be dynamically loaded with the FLUENT solver to enhance the standard features of the code. UDFs are written in the C programming language. The user defined function (UDF) for linear anisotropic phase function, Rayleigh phase function and temperature profile $T_g= T_{max}\times\exp(-y/L)$ are written in C programming language. First of all UDF have interpreted or compiled, the name of the function supplied as DEFINE macro argument will become visible and selectable in the user defined function panel in FLUENT. The linear anisotropic phase function or Rayleigh phase function is hook into the Material panel by selecting user defined in the drop-down list for scattering phase function. The UDF for temperature profile is hook into boundary condition panel.

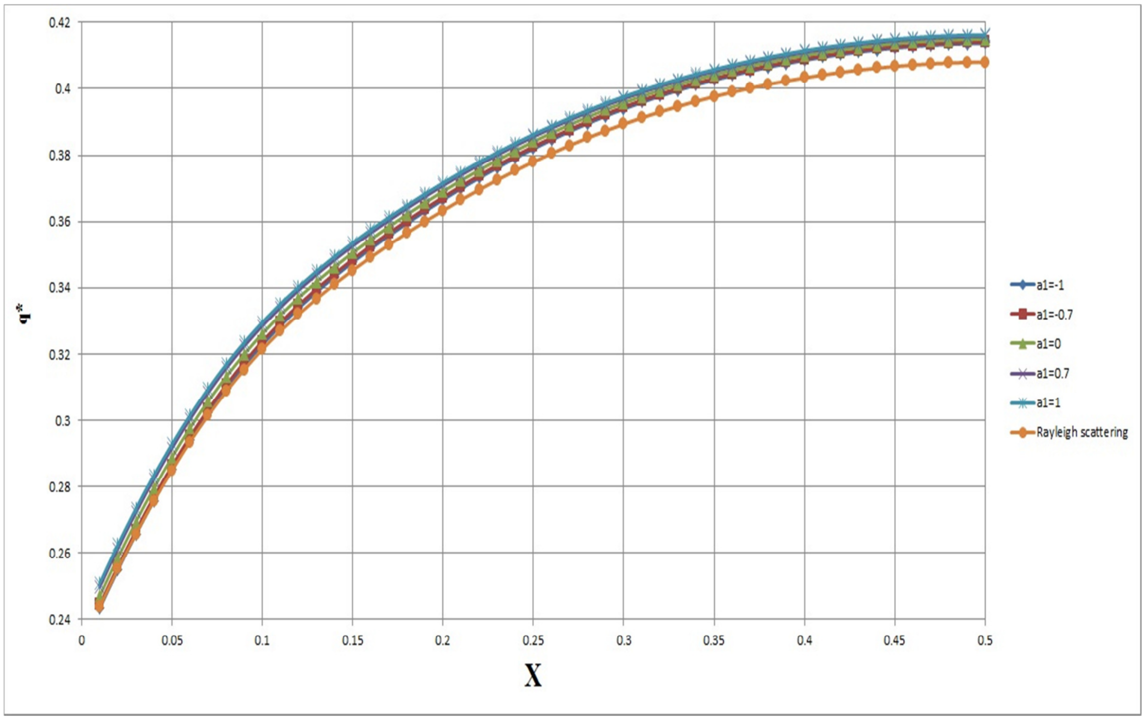
- **Absorbing, emitting, and scattering medium**

The square enclosure is filled with the absorbing, emitting and scattering medium. The dimension of the square enclosure is 1 m×1 m.The domain is discretized into 100×100 uniform control volumes in the X and Y directions. Angular discretization is used that of 1×8 control angles with uniform $\Delta\theta$ and $\Delta\varphi$ in the θ and φ directions respectively. The walls of the square enclosure are black and are at zero kelvin temperature. Here two types of problem are considered. In first problem, the medium is maintained at constant temperature $T_g=T_{max}=300K$. In second problem, the temperature profile inside the medium is $T_g= T_{max}\times\exp(-y/L)$.

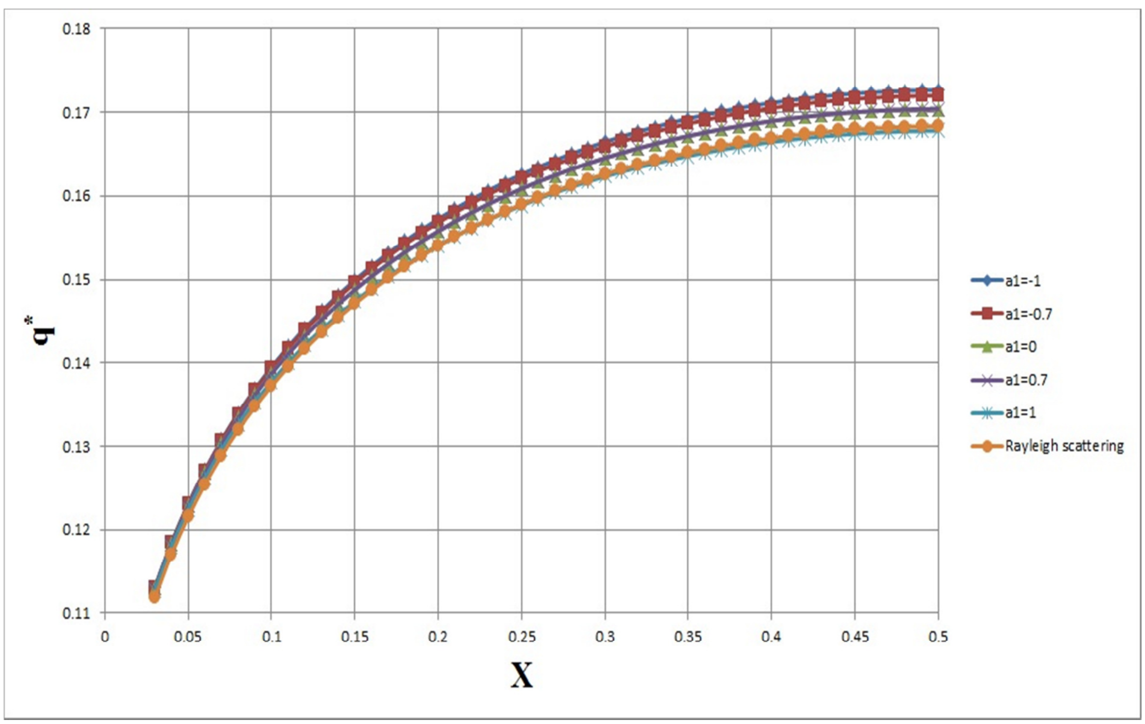
Fig.5.23 shows the effect of linear anisotropic phase function and Rayleigh phase function on dimensionless heat flux along the bottom wall. The absorption coefficient $\kappa=0.5\ m^{-1}$ and scattering coefficient $\sigma=0.5\ m^{-1}$ is taken. Fig. 5.23 shows that the more energy is scattered in forward direction as compared to backward scattering and Rayleigh scattering.Fig.5.24 shows the effect of scattering albedo on dimensionless heat flux along the bottom wall.

- **Scattering medium**

The geometry, grid size, angular discretization, boundary condition, absorption coefficient and scattering coefficient are same as in section 5.2.2. Fig 5.25 shows effect of linear anisotropic phase function and Rayleigh phase function on the dimensionless heat flux.

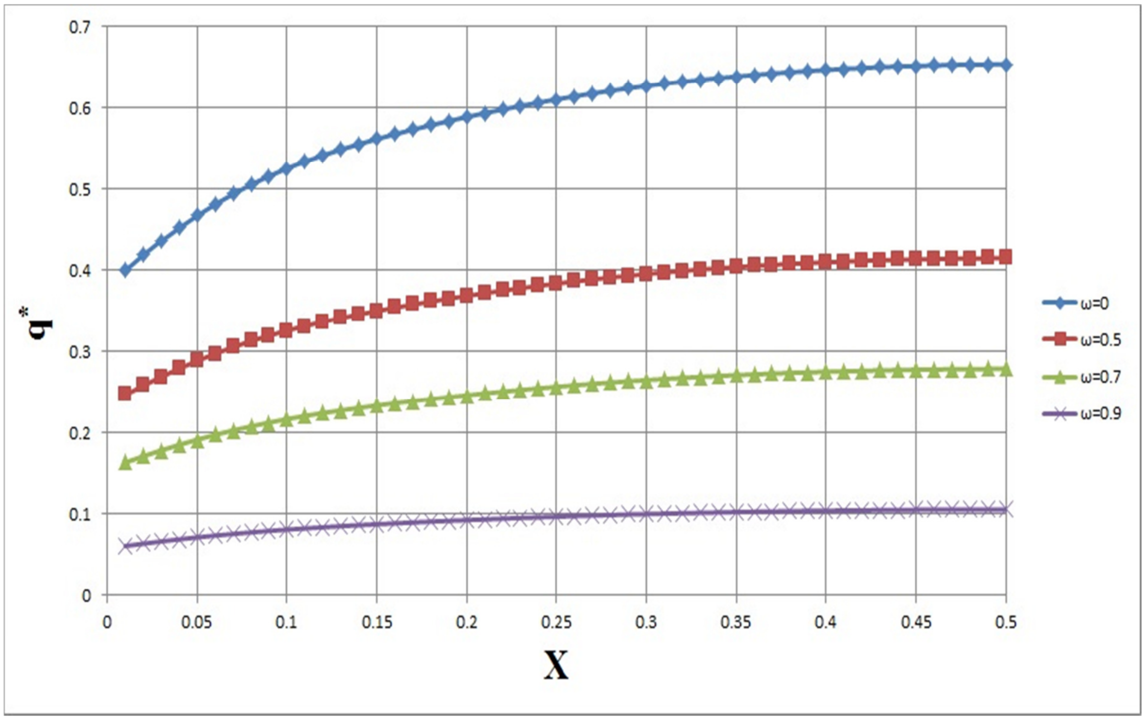


(a)

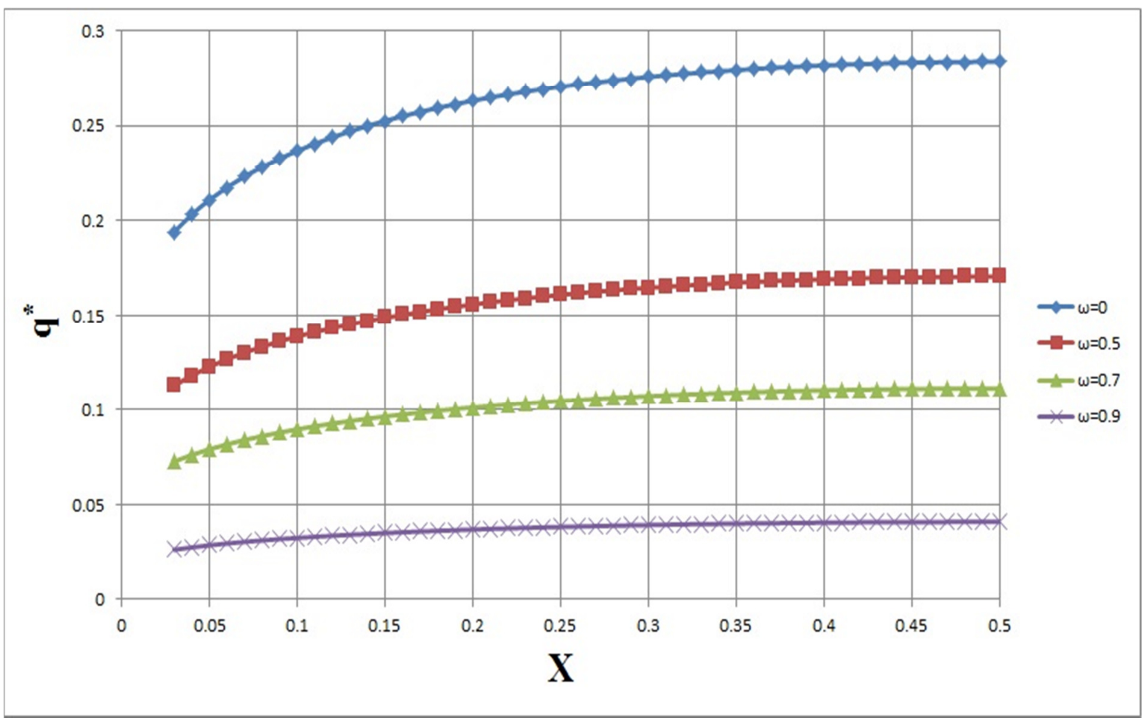


(b)

Figure5.23 Dimensionless heat along the bottom wall for different anisotropic factor and Rayleigh scattering: (a) T_g=T_{max}=300K (b) T_g= T_{max}×exp(-y/L)



(a)



(b)

Figure 5.24 Dimensionless heat flux along the bottom wall for varying scattering albedo: (a) T_g=T_{max}=300K (b) T_g= T_{max}×exp(-y/L)

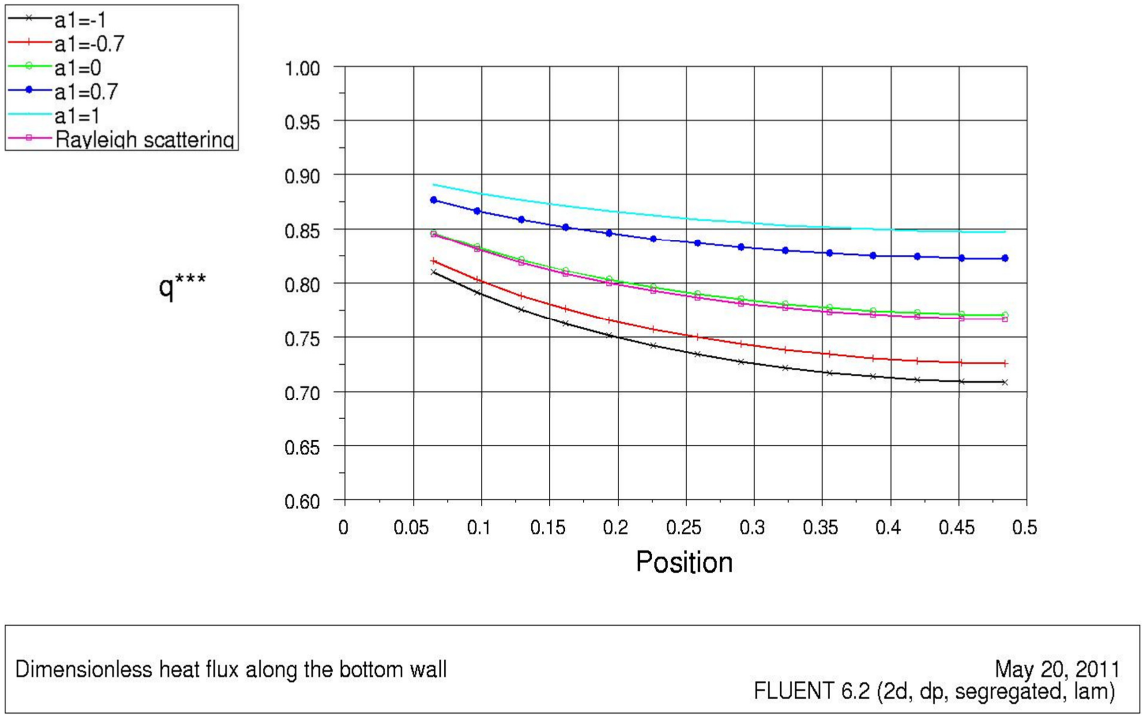


Figure 5.25 Dimensionless heat fluxes along the bottom wall for different anisotropic factor and Rayleigh scattering

Chapter 6

Conclusion and Future work

6.1 Conclusion

In present work, Computational fluid dynamics software package, FLUENT is used. FLUENT which is based on finite volume method are applied to absorbing ,emitting and isotropically /anisotropically medium in two- and three- dimensional problems.

- Results of the present work were validated against those available in the literature. Good agreements were found. Effect of various parameters (absorption coefficient, scattering coefficient, emissivity, scattering albedo, and anisotropic factor) on heat flux and temperature has been analysed. Effect of linear anisotropic phase function and Rayleigh phase function has also analysed.
- In isothermal absorbing emitting medium, the dimensionless heat flux and temperature are increases with absorption coefficient. This is due to the more radiation heat flux is transferred through the walls and fraction of heat flux is absorbed. This absorbed energy is converted into internal energy. That's why the temperature and heat flux is increases.
- In purely scattering medium, when coarse grid is used, FVM overpredicts the heat flux, but it approaches the exact solution with fine grid. The bottom wall is black and the emissivity on the top wall are varies. The top wall is black, the maximum scattered intensity is absorbed and emit by the top wall. But when the emissivity is increases the reflectivity is decreases .Therefore the radiation heat transfer rate increase.
- In 3-D enclosure, when the absorption coefficient is decreases from 1 to 0.25, the temperature at z=4 m is increases. This is due to when the absorption coefficient is less, the energy absorbed by the medium is less than the more heat flux is reached to the wall (z=4m).

- Finite volume method found to be a suitable method for the simulation of collimated incidence problem with Steady RTE. Both transmitted flux and reflected flux increases; reach their maximum and then decreases. At the middle of the wall the radiation is coming from the medium from all directions except that of wall side, but near the corners we got the wall which reduces the contribution from the medium. That's the reason why it's increasing towards centre of the wall in both the cases.
- In non-isothermal gray participating medium, when the absorption coefficient $\kappa=0.001m^{-1}$, then the medium is nonparticipating and no heat flux is absorbed by the medium. The medium is approximately isothermal. But when the absorption coefficient is increases, radiation temperature is also increase. The emissivity on the bottom wall is increases the radiation temperature also increases. Because the emissivity on the wall is decreases, reflectivity is also increases
- In absorbing emitting scattering case, when scattering albedo is zero the dimensionless heat flux is maximum but scattering albedo increases dimensionless heat flux is decreases because scattering albedo is increases the energy loss due to out-scattering is increases.

6.2 Future work

- The two and/or more medium can be used with different refractive index.
- The three dimensional cylindrical medium and irregular geometry filled with absorbing, emitting and scattering medium
- The isotropically and/or anisotropically scattering inhomogeneous medium is bounded by two parallel surfaces.

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