INTERNATIONAL CENTRE FOR HEAT AND MASS TRANSFER

INTERNATIONAL SYMPOSIUM ON

RADIATIVE HEAT TRANSFER

BOOK OF ABSTRACTS

AUGUST 14-18, 1995

KUŞADASI, AYDIN, TURKEY

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* Welcome (M. Saglam, Head of Council of Higher Education of Turkey)

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CHAIRMAN : J.R. Howell
University of Texas, Austin, TX
National Science Foundation, U.S.A.

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Purdue University, West Lafayette, IN, U.S.A.

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University of Kentucky, Lexington, KY, U.S.A.

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ENSMA, Futuroscope, France

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Brigham Young University, Provo, UT, U.S.A.

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Academy of Sciences, Moscow, Russia

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INTERNATIONAL SYMPOSIUM ON

RADIATIVE HEAT TRANSFER

ABSTRACTS

SESSION 1

RADIATION TRANSFER IN MATERIALS PROCESSING AND MANUFACTURING

CHAIRMAN: J.R. Howell

University of Texas, Austin, TX

National Science Foundation, U.S.A.

TR9700083

RADIATION HEAT TRANSFER IN MANUFACTURING AND MATERIALS PROCESSING

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The University of Texas at Austin, Austin, USA
**School of Mechanical Engineering
Purdue University, West Lafayette, USA

ABSTRACT. This review discusses radiation heat transfer which occurs in conjunction with a variety of manufacturing and materials processing applications. Practical needs in manufacturing and materials processing thermal analysis are noted, and the role of radiation heat transfer in meeting these requirements is discussed. Specifically, different types of radiative heating strategies are categorized, radiation sources commonly used are described, and issues which are somewhat unique to radiation heat transfer in manufacturing and materials processing operations, such as matching the spectral characteristics of the source and load, are identified. The need for development of robust inverse analysis tools for process and equipment design, as well as thermal process control is noted throughout the review.

Surface radiation heat transfer, although fairly well understood in principle, is used in many manufacturing operations (such as in electronics manufacturing) and needs for improved understanding and development of new analysis techniques are discussed. Specific topics include i) the practical need for improved surface exchange analysis techniques in complex geometries and/or in systems involving moving materials, ii) coupled macro- and microscale radiation heat transfer for process analysis, thermal control and inspection, and iii) forward analysis and identification of dimensionless parameters describing highly coupled and multiple mode heat transfer operations.

Volumetric radiative transfer in semitransparent materials at high temperature, important in a number of specific operations, such as fabrication of composite epoxy-fiber structures, crystal growth and glass manufacturing, is described. Here, the examples are selected to illustrate i) the importance of matching source and load spectral characteristics, ii) combined volumetric radiative and surface convective heating utilizing flames and other high temperature sources, and iii) the relevance and impact of dependent scattering phenomena.

Finally, needs and challenges in radiation thermometry in practical systems involving, for example, i) moving materials, ii) materials of high purity, or iii) radiatively participating process and/or plant gases are discussed, and recent advances in radiation thermometry theory and applications are reviewed.

RADIATION-CONVECTION INTERACTIONS IN SOLIDIFICATION OF SEMI-TRANSPARENT CRYSTALS

M. Kassemi
Processing Science &Technology Branch
NASA Lewis Research Center
Cleveland, Ohio

M.H.N. Naraghi
Mechanical Engineering Department
Manhattan College

ABSTRACT

This paper studies the interaction of radiation heat transfer with conduction and convection during solidification of semitransparent oxide crystals. A comprehensive numerical model is presented for solidification of two important oxide crystals, BSO and YAG, by the vertical Bridgman technique. Bismuth Silicon Oxide (BSO) is an optically active semi-insulating material that is photoconductive and has widespread applications in optical information processing and computing components, such as spatial light modulators and volume holographic optical elements and filters. Yttrium Aluminum Oxide Garnet (YAG) is another important optically active oxide crystal which is used in many laser devices. These two materials were chosen because they have well-defined experimental counterparts and their thermophysical and radiative properties are relatively well-known.

A schematic of the Bridgman crystal growth configuration is shown in Fig. 1. In solidification of semiconductors, usually both the crystal and the melt are opaque to thermal radiation. Furthermore, both phases typically have relatively high thermal conductivities. Therefore, conduction is the dominant mode of heat transfer in both the solid and the melt. Oxide crystals, on the other hand, are usually semi-transparent to thermal radiation in the solid phase and almost opaque in the melt. They also have relatively low thermal conductivities in both phases. Therefore, heat transfer during the solidification of oxide crystals is governed by an intricate balance between convection and conduction in the melt and conduction and radiation in the solid. In a sense, the solid acts as a light pipe through which the interface loses a considerable amount of heat (by emission) to the cold sections of the crucible wall or directly to the furnace (if the crucible is also transparent).

A radiation heat transfer model is developed based on exchange factors for multi-dimensional complicated geometries encountered in crystal growth. The radiation model takes into account the wavelength-dependant semi-transparency of oxide crystals such as BSO and YAG which are transparent to radiation below 6 microns and opaque to radiation in the rest of the spectrum. It is shown that the radiation model can be easily incorporated into existing finite element codes for fluid flow and heat transfer such as FIDAP. During numerical simulations the algorithm tracks

the position and shape of the interface as the solidification process proceeds and updates the radiation exchange factors based on the changing geometry.

The model was applied to the processing of both YAG and BSO under realistic experimental conditions. From the numerical simulations the following conclusions can be drawn:

1. Under the experimental conditions considered in this paper, radiation is the dominant heat transfer mode at the interface for solidification of BSO and YAG.

2. For both BSO and YAG, the interface attains a highly stretched parabolic shape largely because of the nonuniform radiative loss from the interface. In both cases, the interface is convex into the melt and there are two vortices rotating near the interface with the flow rising from the region near the wall as shown in Fig. 2a.

3. If radiation is neglected or the crystal is treated as opaque, the interface is only very mildly curved due to the mismatch among the thermal conductivities as shown in Fig 2b. The interface is usually convex into the phase with the lower conductivity. In the absence of radiation effects, the flow structure indicates two large vortices in the upper portion of the melt and two smaller vortices near the interface. The direction of the rotation of the smaller vortices depends on the shape of the interface.

4. For YAG, because of its higher conductivity, conduction and radiation are the dominant heat transfer mechanisms. For BSO, convection plays a more important role and the recirculating flow can compensate for a significant amount of the radiant heat loss from the center of the interface rendering a much flatter interface in comparison to YAG.

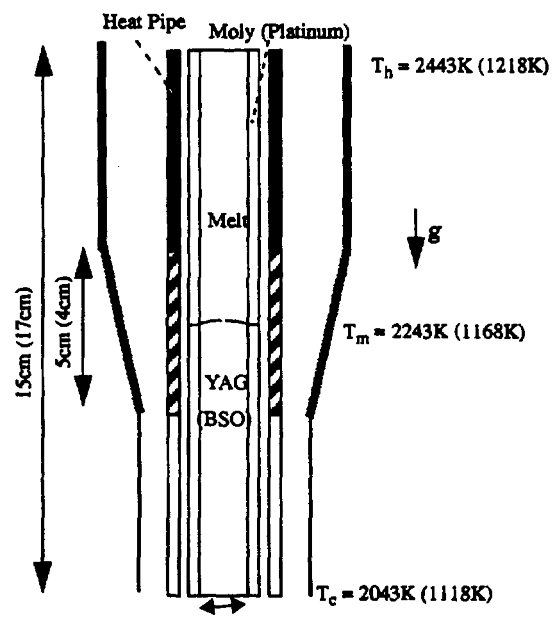

Figure 1: Cross Sectional View of the Crucible in a Vertical Bridgman Furnace.

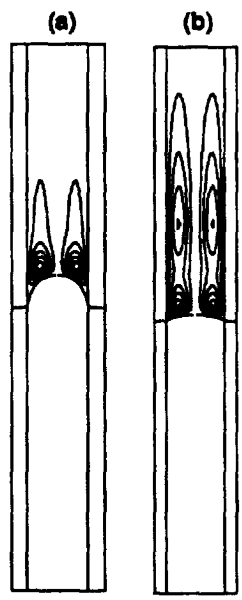

Figure 2: Solidification of YAG for Gr = 2053: a) Radiation Effects (Semitransparent Crystal), b) No-Radiation (Opaque Crystal).

TR9700085

THERMAL TRANSPORT IN OPTICAL FIBER MANUFACTURING

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Dept. of Mechanical Eng., Aeronautical Eng., and Mechanics
Rensselaer Polytechnic Institute
Troy, NY, USA

ABSTRACT. A numerical model of combined radiative and convective heat transfer in a fiber draw furnace was formulated and solved. The model was used to predict glass temperatures and identify important heat transfer modes. The energy equation, which included conductive, convective, and radiative terms, was discretized using a control-volume-based finite element technique. Thermal radiation within the glass was approximated by the P_1 method using a two-band spectral absorption coefficient. Surface-to-surface radiation from the muffle wall to the outer surface of the glass was computed by a full enclosure analysis. A cosinusoidal glass profile was assumed and a continuity-satisfying velocity field was specified.

The results of the calculation showed that radiation was an important mode for air, argon and carbon dioxide purge gases, but that conduction was dominant for the case of a helium purge gas. The glass preform attains its asymtotic temperature higher in the furnace with helium than with any of the other gases studied. Temperatures are relatively insensitive to final fiber velocity and to the spacing between the glass and the furnace wall.

SESSION 2

SOLUTION OF RADIATIVE TRANSFER EQUATION I

CHAIRMAN: N. Selçuk
Middle East Technical University
Ankara, Turkey

TR9700086

A PARABOLIC FORMULATION OF THE DISCRETES ORDINATES METHOD FOR THE TEATMENT OF COMPLEX GEOMETRIES

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Unversität Karlsruhe, Karlsruhe, Germany

[**]School of Mechanical Engineering
Purdue University, West Lafayette, USA

ABSTRACT. Among the various methods proposed for numerically solving the radiative transfer equation, the discrete ordinates method is presently judged as one of the most promising. The usual procedure in the method is to solve one first order differential equation for each of the discrete directions. The numerical treatment of these first order differential equations is well known for its convenient programming and its small computer memory requirements. However, this approach possesses some major shortcomings. The most serious one is due to the nature of the differential equations (first order, hyperbolic type). The method is difficult to implement in advanced finite volume or finite element codes for combusting flows which are designed to handle complex geometries.

In order to overcome this disadvantage, an alternate methodology based on the even parity formulation of the discrete ordinates equations is proposed. This approach leads to a set of second order differential equations as governing transfer equations. The equations are of the parabolic type and their structure is formally similar to the differential equation describing a diffusion process. Hence, this formulation of the discrete ordinates equations is compatible with the numerical structures employed by computer codes for combusting flows.

The parabolic formulation of the discretes ordinates method has been implemented in a computer program for three-dimensional combusting flows developed at the Univerity of Karlsruhe. The code is based on a finite volume formulation and can handle complex geometries by using body-fitted, non-orthogonal grids.

The major objective of the paper is to demonstrate the capabilities of the method. As basic evaluation, sample calculations of benchmark solutions are presented. The test cases are definied on a Cartesian coordinates system. The results reveal that the achievable accuracy of the method is comparable to the conventional discrete ordinates method.

[†]Presently Visiting Assistant Professor at Purdue University

With respect to the application of curvilinear, bodyfitted grids, special emphasis is placed on the various effects encountered when a non-orthogonal grid is used. As a typical example, the rotation of the grid with respect to the principal corrdinates system has been studied. It was found to have an unexpected effect on the radiative flux distribution. A close examination reveals that this effect is related to the directional biasing inherent to the angular quadrature scheme.

Finally, ray effects which are well known to be present in the conventional discrete ordinates method were studied. It was found that they are also present within the parabolic formulation of the discretes ordinates method and that they may be suppressed by applying higher order quadrature schemes.

RADIATIVE-CONDUCTIVE HEAT TRANSFER IN AXISYMMETRIC SEMI-TRANSPARENT SHELLS USING THE DISCRETE ORDINATES METHOD

by **Rodolphe VAILLON, Michel LALLEMAND and Denis LEMONNIER**

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Since the pioneering works of the 60's [1-2], the Discrete Ordinate Method (DOM) has become of a widespread use in the heat transfer community during the last decade. However, it has so far mainly been applied to cartesian geometries and its extension to curvilinear systems is still limited to cylindrical or spherical coordinates [3-4-5]. In particular, we are not aware of any previous works where the DOM is implemented for general orthogonal curvilinear coordinates.

One of the major difficulties of the DOM in non cartesian geometries is the so-called angular redistribution which appears in the RTE when expressed in a given direction and then projected over the coordinate axes. Extra directional terms arise from the fact that the orientation of the local system varies with the position in the spatial frame. As a consequence, a same direction is seen under various angles at different locations. Furthermore, for non cartesian geometries, the integration of the RTE over a controle volume may lead to incorrect results since the space derivative of a constant intensity will in general not give zero [6]. Thus, it requires a specific task to formulate the discrete ordinate method in curvilinear coordinates.

A general expression for the pathlength derivative of radiation intensity is given for spatial directional orthogonal curvilinear coordinates system. The main steps involved in the DOM are described in the case of the configuration described in Fig. 1. As an application the DOM is used for solving the coupled radiative-conductive heat transfer problem in an absorbing-emitting (but non scattering) gray medium confined between two axisymmetric shells whose generatrices are either ellipses or paraboles. The chosen thermal boundaries conditions are temperature or fluxes assessments and the radiative properties of the shells can be black or diffusely reflectives. The problem is solved for a set of curvilinear coordinates (s,n) moving along the inner wall.

Results are given in terms of temperature mappings and fluxes profiles for various values of the optical thickness and of the Planck number.

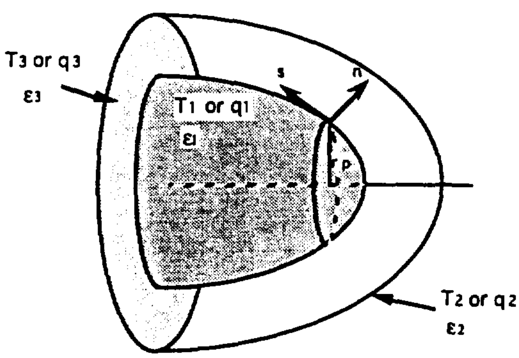

Fig. 1: the problem under consideration and its associated curvilinear coordinates system

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APPLICATION OF THE SECOND ORDER DISCRETE ORDINATES METHOD TO A RADIATION PROBLEM IN A SQUARE GEOMETRY

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ABSTRACT. Radiative heat transfer in a two dimensional square enclosure containing gray absorbing/emitting and nonscattering media was investigated to explore validity of the second order discrete ordinates method which had been reformulated from the conventional discrete ordinates (S_N) method. Discretizaton equations of governing equation and boundary condition were obtained using a Taylor series expansion method (TE) and using an exponential scheme with cubic interpolation method (EXP3) and the results were compared with those from the conventional S_N method and the zonal computations (in the zonal computations, the direct exchange areas were integrated numerically using the Gauss-Legendre quadrature). Two sample problems were taken ; in the first, the medium has known heat source and the walls are cold (gas emission problem), and in the second, the medium has no heat source and one of the walls is hot while the others are cold (boundary emission problem) ; all the walls are black and diffuse in both problems. The two problems were solved to obtain the medium temperature and the wall heat flux distributions using S_2 and S_6 methods with varying optical depth. When the optical depth is as small as 0.1, S_2 results of the second order and the conventional discrete ordinates method deviate significantly from the zonal one in both problems while the S_6 results of any discrete ordinates method are in fair agreement with the zonal results. When the optical depth is large (10 here), the heat flux obtained from S_6/EXP3 is closer to the zonal result than that of conventional S_6 near the corner in both problems. When the optical depth is unity, an intermediate behavior is observed. On the whole, the second order S_N results show very good agreement with those of conventional S_N method and when the number of discrete ordinates is not too small, they also agree well with the zonal computations. When the optical depth is small in the boundary emission problem, the second order S_N method shows wall heat flux greater than the blackbody emissive power near the corner (TE is worse than EXP3), which calls for further improvement.

CALCULATION OF THE RADIATION FLUX DIVERGENCE NEAR THE REGION OF LOCAL HEAT RELEASE BY QUADROMOMENT METHOD

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Accurate and general solutions of the radiation heat transfer equation in two-dimensional geometry are required for several low temperature plasma applications. To study various radiation transfer calculation methods in two-dimensional cylinder-shaped geometry the stimulating problem is the one of mathematical simulation of radiation processes in the continuous optical discharge, which is used in laser plasma generators and laser sustained rocket engines. As a rule, continuous optical discharge is generated at pressures around the atmospheric level, therefore, the model of local thermodynamic equilibrium may be used as the basis for a radiant heat exchange problem. A typical dimension of the continuous optical discharge is ~1 cm, the temperature in its central part is ~12000-20000 K.

The radiation transfer equation has been modelled by using method of quadromoments for two-dimensional cylindrical geometry. The scattering of heat radiation is disregarded.

The original ideas for method of quadromoments was first given by Ozisik, Menning and Halg[1] (the half-range method for a spherically symmetric geometry), Sherman[2] (the half-moment method for a plane-parallel geometry), Menguc and Iyer[3] (the multiple spherical harmonics approximations for plane-parallel and two-dimensional cylindrical geometries).

At present formulation, the simplest zero-order moments are used to provide a solution of the radiation heat transfer equation for two-dimensional cylindrical volume with high temperature inhomogeneities.

The technique of lowering the order of the system of multigroup equation in the quadromoment form is described. The problem, in essence, is this: integration of radiation transfer equation in a selective formulation or in group approximation (including statistical simulation at sections) for the purpose of determination of the total energy emission rate stipulated by radiation processes provides for multiple solutions in individual sectors of the spectrum with subsequent adding up of the results. This is the main reason for the fact that the labour intensity of solution of selective radiation transfer usually supersedes the labour intensity of solution of the associated mechanical problems. Therefore methods of effective reduction of dimensionalities of the system of selective equations are often used in radiation gas dynamics. The common idea of these methods is that the full system of selective equations is not solved at each stage of solution of gas dynamics equations, but is solved periodically (as the need arises). The main result of solution of this full system of equations is determination of effective coefficients in the transfer equation integrated through the spectrum. It is this last equation that is solved at each step jointly with gas dynamics equations until the given replacement of the system by just one equation becomes too rough. The advantage of the such formulation of the quadromoment method is that unlike methods of averaging by the full solid angle (for example, PN-approximations of Spherical Harmonic method), where the average integral absorption coefficient may have gaps of the second type, the given case presents a smooth continuous functions.

Numerical solutions of the equations for the two-dimensional cylindrical geometry are obtained using a software code and the results are compared with those available by P1-approximation of Spherical Harmonic method. These calculations were made for two temperature distributions: with temperature in the hot area centre $T_1 = 10000K$ and $T_1 = 18000K$. Different calculation grids, absorption coefficients k and coefficients defining the value of artificial calculation diffusion ε were used. It has been established that the zero approximation of the quadromoment method with ε=1-10 in a wide range of optical thicknesses allows to obtain results close to the results based on the P1 approximation of the spherical harmonics. If ε = 0.1 is entered, it leads to incorrect distribution of heat radiative flux divergence in the peripheral area of the volume. Relative error is getting higher as we move further from the central high-temperature area.

A question is discussed as to whether the method of quadromoments can describes the heat radiative flux divergence in low temperature plasma near the regions of local heat release.

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TR9700090

RADIATIVE HEAT TRANSFER OF ARBITRARY 3-D PARTICIPATING MEDIA AND SURFACES WITH NON-PARTICIPATING MEDIA BY A GENERALIZED NUMERICAL METHOD REM^2

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ABSTRACT

Radiative heat transfer of absorbing, emitting and scattering media and of diffuse and specular surfaces containing non-participating media is analyzed by a generalized numerical method: Radiation Element Method by Ray Emission Model, REM^2. 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 view factors.

We consider a system composed of N radiation elements. N elements are divided into M participating media or absorbing and diffuse reflecting surfaces and L non-participating media or perfect specular surfaces. The radiation elements are numerically modeled by arbitrary triangles, quadrilaterals, tetrahedrons, wedges and hexahedrons generated by a general purpose pre- and post-processor package for the finite element method.

Discretized radiation rays are emitted from each participating radiation element according to a ray mission model. The ray tracing is performed for all N radiation elements; however, only M participating elements are considered for view factors and radiation transfer. In the present analysis, the elements are classified into participating and non-participating radiation elements and the memory needed for the calculation is minimized.

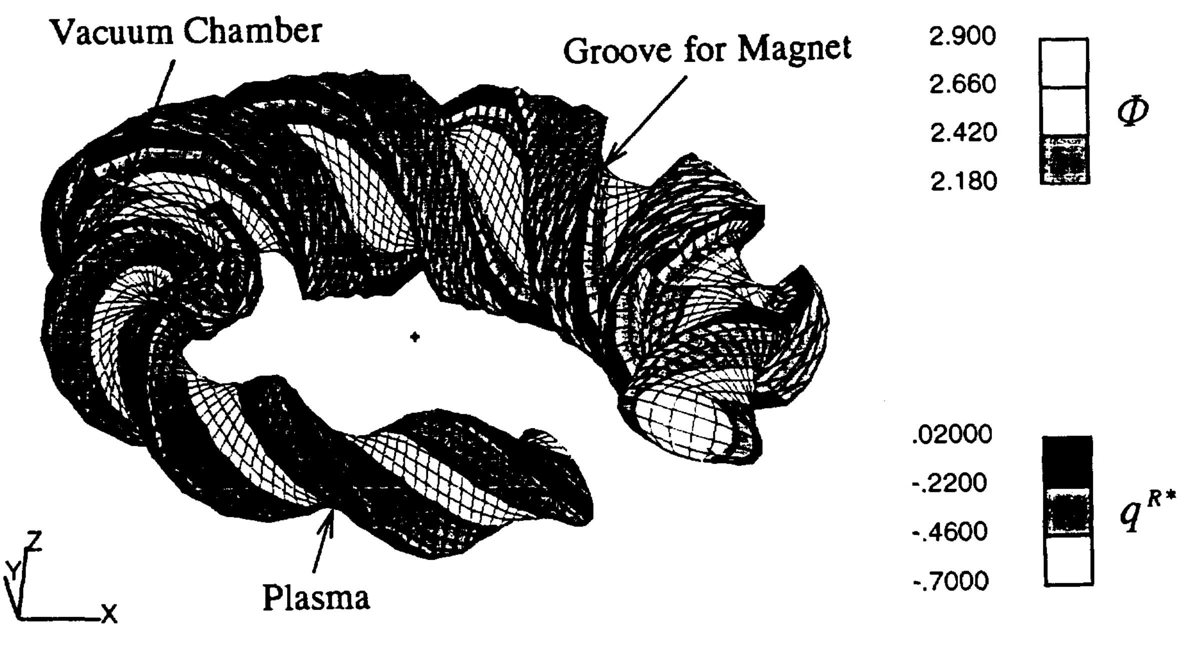
The present method was applied to a two-dimensional participating square and a three-dimensional participating cube covered with black isothermal walls. The results are compared with a semi-analytical solution and the results obtained by a zonal method, respectively. The present method shows good agreement with existing solutions, using only a small number of ray emission and radiation elements. Comparison of the dimensionless temperature distributions of the cubic medium show some deviation between solutions for large and small ray emission numbers. However, the distribution in each case is almost identical except for the very small region near corners.

A spherical participating medium with uniform heat generation contained in a square isothermal and adiabatic walls is analyzed. The temperature in the participating sphere shows spherical distributions for the case of small and medium optical thickness in spite of the non-sherical boundary conditions of the outer wall when the heat generation is uniform in the spherical medium.

As an example of an arbitrary configuration, a torus plasma in a large helical device for

the research of a fusion reactor was analyzed, in which plasma is approximated as a gray participating medium and a specular and diffuse surface is assumed for the vacuum chamber.

The dimensionless temperature distribution of the model plasma and surface heat flux of the vacuum chamber are demonstrated. The dimensionless temperature distribution of the model plasma and the dimensionless surface heat flux are shown in the Figure below. The analysis model is consist of 2430 elements. The figure represents the total model of the helical device comprised of 24300 elements and a part of the wall and plasma are removed to show the distributions. The temperature distribution of the plasma has a maximum value at the center, and a minimum in the region near the end major axis. The heat flux on the wall is negative due to the definition. The distribution shows a maximum flux on the bottom of trapezoidal grooves and has a minimum value at the corner of the edge of the grooves.



Temperature distributions of modeled plasma in large helical device used for study of fusion reactor and the wall heat flux on vacuum chamber.

SESSION 3

SOLUTION OF RADIATIVE HEAT TRANSFER EQUATION II

CHAIRMAN: S. Maruyama
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RECENT BENCHMARKINGS OF RADIATIVE HEAT TRANSFER WITHIN NONHOMOGENEOUS PARTICIPATING MEDIA AND THE IMPROVED YIX METHOD.

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[2]Aerospace Engineering and Engineering Mechanics Department University of Texas Austin, Texas, USA

ABSTRACT: A review of the recent benchmark efforts since the First Symposium on Solution Methods for Radiative Heat Transfer in Participating Media is presented. The Symposium was first held at 1992 28th National Heat Transfer Conference and then at 1994 6th AIAA/ASME Joint Thermophysics and Heat Transfer Conference. Also presented is the continuing effort to improve the solution accuracy of the YIX method for benchmarking. The latest work is focused on multi-dimensional, gray, and nonhomogeneous participating media.

Solution of radiative heat transfer in nonhomogeneous participating media has been an important research subject for many engineering and scientific applications. Most of the applications encountered in actual systems contain participating media with nonuniform radiative property distributions in the multi-dimensional geometries. Computational limitations are presently a major factor in dictating the present state-of-the-art since modeling real properties and geometries is very computationally expensive, usually much more expensive than the flow simulations in the same system. Due to the integro- differential nature of the radiation transport, many algorithms, many more than those for the Navier-Stokes equations, have been developed in the past to solve the radiation transfer equation (RTE). Although many methods, such as the discrete ordinates method, the Monte Carlo method, the finite element method, the finite volume method, and the YIX method, can be applied to arbitrarily complex geometry and spectral properties in principle, little is known on their efficiency and accuracy relative to each other.

Because of the complexity of the RTE and the wide variety of methods available, error estimation of the computations is usually unavailable, and it is not uncommon that large differences can be found in the results for the same problem using different methods. This became apparent at the above mentioned Symposium. In that Symposium, participants were asked to solve a three-dimensional problem consisting of a nongray mixture of spherical carbon particles and CO2 gas contained in a rectangular enclosure. The problem was intended to model a coal-fired furnace. Despite major property and geometry simplifications made in defining the problem, larger-than-expected variations in the predictions were found. Similar situations can be found in journal publications where large differences among results are not unusual.

Therefore, it is critical to provide some benchmark solutions to the radiation heat transfer community. The need for benchmarks has been also reflected in a recent workshop on the use of high- performance computing to solve participating media radiative heat transfer problems (held in March 1993 at the Sandia National Laboratories), in which participants were asked to identify 5 classes of highly challenging, nationally important problems relating to the use of high-performance computing in the participating media radiative heat transfer. The first problem identified is the development of benchmark solutions for RTE.

Following the first Symposium in 1992, the YIX method has been used in a separate benchmarking effort with the Monte Carlo and the finite element methods. They are used to solve the radiative heat transfer within a unit cubical enclosure with nonhomogeneous participating media. With the first order accurate distance quadrature and piecewise constant integrand, the YIX solutions show 1 to 3% difference of surface heat fluxes in cases E1 and E2 as compared with the finite element solutions on the same grid. [1]

Cases E1 and E2 have uniform temperature distribution inside the cold and black enclosure. Using the same piecewise constant radiative property distribution as the YIX solutions, the Monte Carlo solutions have the same order of error. It is also found that the YIX solutions have bigger difference at the core region where the optical thickness is larger.

In this paper, three higher order interpolation schemes, i.e., piecewise linear, trilinear, and parabolic, are presented to improve solution accuracy in generating benchmarks with YIX method. Detail and systematic er-

[1]Hsu, P. and Farmer, J. T., Benchmark Solutions of Radiative Heat Transfer within Nonhomogeneous Participating Media Using the Monte Carlo and YIX Methods, presented at the 30th National Heat Transfer Conference, Portland, Oregon, August 5-8, 1995.

ror analyses indicate that superconvergence exists for these interpolations. Especially notable is the piecewise trilinear interpolation. It has excellent convergent rate as compared with the order of its interpolation error. The result shows that one order of magnitude reduction in error can be achieved without resorting to finer grid. Significant computational time and memory can be saved with high order interpolation. This has important implications when coupling the RTE calculation with the flow code.

Other than the interpolation error, the integration errors of the YIX method, which include distance and angular quadrature, are also examined. The use of discrete ordinates set in the angular quadrature is studied rigorously and compared with the use of Simpson rule. The convergence rate of the discrete ordinates sets is superior due to its spherical symmetry.

A related issue with angular quadrature is the ray effect. It is shown that for the problem that could cause ray effect in the solution, the effect can be eliminated by using large number of angular quadrature points. It is further determined that an adaptive angular quadrature scheme has the potential of removing ray effect without significant increase of the computational time. On the other hand, the use of high order distance quadrature is found that, without the corresponding higher order interpolation, little benefit can be obtained from it. The main intent of these results is to provide a verified set of solutions which can be useful as benchmarks when developing other methods.

EVALUATION OF DISCRETE TRANSFER MODEL FOR RADIATIVE TRANSFER IN RECTANGULAR FURNACES

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ABSTRACT The Discrete Transfer Model was applied to the prediction of the radiative flux density and source term of a box-shaped enclosure problem based on data reported previously on a large-scale experimental furnace with steep temperature gradients typically encountered in industrial furnaces. The rectangular enclosure under consideration has interior black walls and an absorbing emitting medium of constant properties. The predictive accuracy of the model was evaluated by comparing its predictions with exact numerical solutions produced previously for the same enclosure problem. The comparisons show that the model provides radiative flux density distributions in close agreement with the benchmark solutions. However, with regard to the distributions of radiative energy source term, a relatively poor agreement is obtained. Evaluation of the accuracy of the Discrete Transfer Model against exact solutions on a rectangular enclosure problem with a steep temperature gradients is not available to date.

To be presented in the "First International Symposium on Radiative Heat Transfer" 14-19 August 1995, Kuşadası, Türkiye

Abstract of paper presented at the
International Symposium on Radiative Heat Transfer
14-18 August, Kusadasi, Turkey

Three-dimensional Spectral Radiative Transfer Calculation in a Cylindrical Model Combustor Using the Discrete Ordinates Method

by

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One of the basic requirements of modern combustor design is a detailed knowledge of the heat load of the combustor walls. Since high flame temperatures and high optical densities due to high pressures or large geometrical scales are encountered, in most combustion systems a considerable part of the wall heat load stems from radiation.

For the calculation of the multidimensional spectral radiative heat transfer quite a lot of models have been suggested to describe the radiative properties of combustion gases and soot as well as the multidimensional radiative exchange. Recently, the different approaches to determine multidimensional radiative heat exchange have been evaluated separately at the Institut für Thermische Strömungsmaschinen (ITS) in special test cases. It has been found that the Discrete Ordinates method should be best suited to combustion systems with respect to accuracy and computation time. However the Discrete ordinates method has not been evaluated in real combustion systems.

Therefore, the main objective of this paper is the application of the Discrete Ordinates method to calculate the multidimensional radiative heat transfer in a "real" propane fired three-dimensional cylindrical model combustor featuring high gradients of temperature and concentrations of radiative active species. The information about the reacting flow-field inside this model combustor has been provided by both experiments and numerical analysis.

The radiation calculations are performed on a spectral basis using narrow-band models for an accurate representation of the radiative properties of combustion gases. To avoid "sweeping" in angular space the Discrete Ordinates Equations describing radiative exchange in a three-dimensional cylindrical coordinate system have been discretized by a "purely" spatially applied Finite Volume technique for the first time. This has been achieved by formulating the discrete direction vector in cylindrical coordinates, too.

The different applied S_n-approximations (S_4, S_6, S_8) are evaluated by comparing the calculated spectra to measured spectra and calculated spectra obtained from 1D-calculations which serve as reference data. It has been proven, that multidimensional spectral radiative heat transfer in a real cylindrical combustion system featuring steep gradients of temperature and concentration of radiative active species can be predicted accurately using the models presented. As expected, the calculations of radiative heat transfer through the reaction zone is most critical, due to the steep gradients of scalar variables. However, using a fine grid size of 18998 grid points, highly accurate results are already obtained by application of the S_4-approximation. Therefore considering CPU-time consumption and accuracy, the S_4-approximation is best suited to radiation calculations in combustors.

TR9700094

THREE-DIMENSIONAL ANALYSIS OF RADIATION HEAT TRANSFER IN A RADIANT COOLED SPACE

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ABSTRACT. The objective of this paper is to develop an analysis method of local radiation heat transfer in a radiant cooled space containing arbitrarily shaped objects. In this paper, the following methods are proposed. The surfaces of the objects are divided into small quadrilateral subsurfaces. Radiation view factors between subsurfaces are calculated by combining the Mitalas-Stephenson contour integration method and a simple method for judging obstructions. Then the radiation heat exchange on each subsurface is obtained using Gebhart's enclosure analysis method. Heat transfer by convection, conduction and ventilation is considered in the calculation in addition to radiation. We can obtain the steady-state temperature of each subsurface by solving the nonlinear heat balance equations using Newton-Raphson and Gauss-Seidel methods.

By using above methods, the steady-state cooling environment of a meeting room with a cooled ceiling panel is analyzed. The local thermal influence of a heated window on the cooling environment is examined. In the analysis, a three-dimensional model of a human body is also used. It is divided into three parts: head, body and legs. The skin temperature and clothing combination can be assigned to each part of the body independently. The thermal sensation of the human body in the room is evaluated quantitatively by calculating the heat loss of the human body and the predicted mean vote (PMV).

Our analysis method contributes to the systematic design of the radiant cooled space. It can determine the arrangement of furniture and the temperature of the cooling panel to obtain satisfactory thermal sensation in the space. It also enables us to improve the environment where thermal radiation sources such as heated windows cause thermal discomfort.

DIRECT EXCHANGE AREAS FOR AN INFINITE RECTANGULAR DUCT BY DISCRETE-ORDINATES METHOD

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ABSTRACT

The purpose of this study is to compute direct exchange areas (DEA) for an infinite rectangular duct by using the discrete-ordinates method. A gray absorbing and emitting medium is enclosed by opaque black walls. The system may have a protrusion on the sufaces and that causes shadings between surfaces.

DEA's of the system are calculated. The discrete-ordinates weights are expressed in terms of the product of cross-sectional weights and axial directional weights. For the cross-sectional weights and directions, Sanchez and Smith's method or Chevyshef method is used. The abscissas and weights of Gaussian quadrature are utilized for axial direction integration to incorporate absorbing and emitting effects by the infinite layer.

The effects of optical thickness as well as the number of spatial and angular divisions on the accuracy of the DEA results are studied. The results are presented at the optical thickness values of 0, 0.1, 1, and 10. When optical thickness is greater than 5, if the relative errors of DEA values should be less than about 2 %, then it is needed more spatial and angulare divisions than current study. As optical thickness increases at a given spatial and angular divisions, the errors increase. For a given optical thickness, the errors are reduced as the number of spatial and angular divisions increase. If there is shading due to protrusion in the system, the accuracy of the results depends on both the number of spatial and angular divisions.

The results are compared with the DEA prediction by the S-N discrete-ordinates methods of order upto S-10. The results indicate that the higher order S-N method than S-10 is necessary to increase the accuracy of computation. The results are also compared with the numerical integration values of the DEA's expression. In conclusion, whether there is shading in the system or not, direct exchange areas can be accurately obtained by using the discrete-ordinates method.

RADIANT FLASH MELTING OF MICRON POLYMER-PARTICLES

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ABSTRACT. The transitions of radiation properties of a toner-particle bed during the fusing process in electronic printing were investigated. The bidirectional transmittance and reflectance for the bed before fusing, a slightly fused bed and the completely fixed bed were measured. The radiation properties were estimated, as an inverse problem, from a comparison between the experimental and numerical results. The results show that the optical thickness and the scattering albedo vary during the fusing process, depending on the change of the shape of the toner particle.

1. INTRODUCTION

Electronic printing is performed through the processes of corona charging, exposure with a light and lenses, development into a visible image with a toner powder, transfer to a paper, fusing and fixing of the toner on the paper, cleaning and erasing. The toner is a mixture of resinous binders, coloring agents, magnetites, lubricants, and other additives; where the thermoplastic resins are the main components of the toner. The physical properties of the toner particle are not easily available. The best combination is empirically determined, taking the types of the development and fusing into account. The printing speed is principally controlled by fusing process of the toner powder on a paper. Four kinds of methods, i.e., hot rolling, fusing in an oven, pressurized rolling and radiant flash fusing, are investigated, associated with several kinds of the toner powder, for the past few decades. Of these, it is considered that the radiant flash fusing is the most useful method for high speed printing. However, no phenomenological work has been reported on the fusing process through the radiant heating. The toner powder on the paper is regarded as a packed bed. A regime map for independent and dependent scattering is depicted with respect to the size parameter and the volume fraction. However, the results are for sphere particles. On the other hand, the toner particle before fusing is not a sphere, and the shape is expected to change at a temperature above the softening point. In addition, some additives are also able to absorb and scatter the radiation. In the present study, the transitions of radiation properties of the toner bed during the fusing process have been investigated through the measurements of the bidirectional transmittance and reflectance and through the numerical calculation.

2. EXPERIMENT

The spectral bidirectional transmittance and reflectance, and the spectral normal directional transmittance are measured for a toner particle bed before fusing, for a slightly fused bed and for a completely fixed bed. The wavelengths of the incident beam are 0.6, 0.8 and 1 μm. The mean size (equivalent diameter) of a particle and the mean thickness of the bed, as measured by a scanning laser microscope, are 9.2 and 31.7 μm, respectively. The volume fraction is 0.28. The scattered light is measured using a photo sensor mounted on an optical rail. Thereby, the azimuthally symmetric radiation field can be measured by traversing a single plane, where the azimuthal symmetry is confirmed through the comparison between scattered light intensities at two different azimuths.

3. ANALYSIS

Thermal radiation is absorbed and scattered by toner particles, i.e., the thermoplastic resin, magnetites, coloring agents and other additives. Furthermore, the shape of the toner particle changes from a non-spherical to almost a spherical particle, and then to almost a slab. Therefore, it is impossible to specify what is the main scattering and/or absorbing materials, and what is the dominant phenomena, i.e., the surface reflection, refraction or Mie scattering by small additives, in each step during the fusing process. For analysis, in the present study, the medium is treated as a pseudo-continuum to clarify the global absorbing and scattering processes. The emission of radiation is assumed negligibly small. The Henyey-Greenstein approximation is used for the scattering phase function. As a result, the unknown parameters in the radiative transfer equation are the optical thickness, the scattering albedo and the asymmetry parameter of the phase function. Of these, the optical thickness is estimated from the normal directional transmittance on the basis of the Beer's law using a fine incident beam. Other parameters are estimated from a comparison between the profiles of the bidirectional reflectance and transmittance for measurement and calculation.

4. RESULTS AND DISCUSSION

Through fusing process, the shape of the particle changes from a non-spherical to a spherical one, resulting in the decrease in the projected area of the particle. Simultaneously, the transparency of the particle becomes increased. On the other hand, the completely fixed bed dose not have so many pores transmitting the radiation through the bed. As a result, the optical thickness of the toner bed first decreases and then increases during the fusing process. That is, the optical thickness is strongly dependent on the total projected area of the particles. Furthermore, both the scattering albedo and the asymmetry parameter of the slightly fused bed are higher than those of the bed before fusing since the surface of the particle becomes smooth through fusing. For the completely fixed bed, the scattering albedo is considerably small compared with those of other beds. For the bed before fusing, the surface of the particle has a roughness with several different characteristic heights. The surface, which is optically rough for short wavelengths, can be smooth at long wavelengths. As a result, the bidirectional transmittance and reflectance increase with wavelength ranging from 0.6 to 1 μm. On the other hand, the values of the normal directional transmittances are almost the same over the range of the wavelength since the scattering cross section dose not change. Although the effect of the additives, such as magnetites and coloring agents, is not clarified in the present study, it is expected that the materials strongly contribute to the scattering and absorption of the radiation when the transparency of the toner particle becomes high; that is, in the cases of the slightly fused bed and the completely fixed bed. Consequently, the amount of the radiant energy absorbed by toner bed varies with time in the flash melting process.

Acknowledgement

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SESSION 4

TRANSIENT RADIATION PROBLEM AND RADIATION/TURBULENCE INTERACTIONS

CHAIRMAN: J. Taine
Ecole Central Paris
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TWO-FLUX AND GREEN'S FUNCTION METHOD FOR TRANSIENT RADIATIVE TRANSFER IN A SEMITRANSPARENT LAYER

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ABSTRACT. A method using a Green's function is developed for computing transient temperatures in a semitransparent layer by using the two-flux method coupled with the transient energy equation. Each boundary of the layer is exposed to a hot or cold radiative environment, and is heated or cooled by convection. The layer refractive index is larger than one, and the effect of internal reflections is included with the boundaries assumed diffuse. The analysis accounts for internal emission, absorption, heat conduction, and isotropic scattering. Spectrally dependent radiative properties are included, and transient results are given to illustrate two-band spectral behavior with optically thin and thick bands. Transient results using the present Green's function method are verified for a gray layer by comparison with a finite difference solution of the exact radiative transfer equations; excellent agreement is obtained. The present method requires only moderate computing times and incorporates isotropic scattering without additional complexity. Typical temperature distributions are given to illustrate application of the method by examining the effect of strong radiative heating on one side of a layer with convective cooling on the other side, and the interaction of strong convective heating with radiative cooling from the layer interior.

TR9700098

Transient Radiative Transfer

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Abstract

This paper outlines the formulation of the transient transport of radiation through scattering absorbing media and discusses the need for developing methods for predicting and evaluating transient radiative transfer. As a first approximation the intensity field is modeled as a linear function of the cosine of the angle, and the coefficients of the linear function are functions of time and position. The mathematical form of the resultant radiative transport equations is of a hyperbolic form with a wave speed equal to $1/\sqrt{3}$ of the speed of light in the medium. The incident source travels at the speed of light. Applications where these results are important include the transport of femtosecond and picosecond laser pulses through absorbing and scattering medium such as in the imaging of tissues or probing the characteristics of particulate medium by examing the transmitted or back-scattered transients.

NUMERICAL INVESTIGATION OF RADIATION AND TURBULENCE INTERACTIONS IN SUPERSONICALLY EXPANDING HYDROGEN - AIR JET

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The axisymmetric Reynolds averaged Navier-Stokes equations have been used to investigate the mixing and reaction of a supersonic hydrogen jet in a co-flowing stream of vitiated air. The numerical method uses a finite volume approach and a quadratic upwind interpolation scheme. The equation system was closed using either the two-equation k-ε turbulence model or the Reynolds stress turbulence model. A four species, one reaction, global finite rate chemistry model is used to simulate the combustion processes. The influence of turbulence on the reaction rate is taken into account by considering finite rate burning based on the rate of decay of large turbulent eddies into small ones. The radiative heat transfer term in the energy equation is simulated using the Discrete Transfer Radiation Model (DTRM). Formulation of the equations of motion, turbulence, chemistry and radiation modeling is discussed.

Extensive parametric studies are conducted to investigate the effects of grid refinement, inlet turbulence intensity, and turbulence models on the prediction of the velocity, temperature and major species concentrations. It is found that there is no significant differences between the RSM and k-ε model prediction of the degree of mixing and combustion. The extent of the mixing is reasonably well predicted by both models. However, some discrepancies between the two predictions and the experiment are indicated, specially along the centerline of the burner and farther downstream of the nozzle. Both models predict a small amount of reaction upstream of the lifted flame base due to mixing with hot vitiated air and combustion takes place farther downstream of the lifted region. This is consistent with the experimental finding in the open literature.

TR9700100

RADIATION-TURBULENCE INTERACTION IN FLAMES USING ADDITIVE TURBULENT DECOMPOSITION

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ABSTRACT: The purpose of this paper is to discuss the nature of the unsteady interactions between buoyant turbulence and radiation feedback to the center of flames. An unfiltered additive turbulent decomposition (ATD) is carried out in a manner similar to that originally developed by McDonough and co-workers for studying Burgers' equation. The new approach is philosophically similar to LES; namely, treat the large and small scales separately. However, the technique requires no formal filtering or averaging for the large-scale equations, and the corresponding subgrid-scale models are obtained as local spectral approximations of the original governing equations. In the present work, only the small-scale part of the governing equations has been solved, and the large-scale parameters are to be obtained directly from either a global computer program or from corresponding experimental results. Preliminarily calculated results show that the radiation in the flame markedly influences the flow in the center of flame, and even periodic radiation fluctuations can lead to chaotic behavior of the flow. The extent to which the flow fluctuates not only depends on fluctuation of radiative properties, but also on the profile of the mean absorption coefficient.

SESSION 5

RADIATIVE PROPERTIES OF GASES

CHAIRMAN: M.G. Carvalho
University of Lisbon
Lisbon, Portugal

ACCURACY OF VARIOUS GAS IR RADIATIVE PROPERTY MODELS APPLIED TO RADIATIVE TRANSFER IN PLANAR MEDIA

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Radiative transfer calculations which take into account each absorption line, i.e. the fine structure of the molecular spectrum, need very important computational times. Several models have been developed to predict gas radiative properties averaged over a spectral range of a finite width varying from a few cm^{-1} to a few hundred cm^{-1} (band models) or over the whole spectrum (global models). The aim of this paper is to compare the accuracy of these models and the computational times required when they are applied to radiative transfer calculations in a simple H_2O-N_2 planar geometry. The studied models are : (i) the line-by-line (LBL) approach which is used as a reference for benchmark comparisons. The spectral resolution is typically 10^{-2} cm^{-1}. LBL calculations are based on the EM2C high temperature spectroscopic H_2O data base which contains line positions, intensities, Lorentz broadening parameters and level energies. (ii) The statistical narrow-band (SNB) model with the exponential tailed-inverse distribution of line intensities. The Curtis-Godson approximation is used for non-homogeneous paths. The considered spectral resolutions of the SNB model are 25 cm^{-1} and an optimized variable resolution. (iii) The correlated-k (CK) model with an optimized variable spectral resolution. (iv) The correlated-k fictitious gas (CKFG) model in which the real gas is considered as a mixture of fictitious gases characterized by lines of similar transition lower state energies. The CK approach is then applied to each gas. This model has been developed especially for highly non-isothermal paths. (v) The weighted sum of gray gases (WSGG) model which is global, contrary to the three previous models. The parameters of the approximate models are adjusted to fit line-by-line transmissivity calculations for various optical paths. Radiative properties of homogeneous and isothermal columns are then practically the same when predicted from all models. In this manner, we compare only the ability of each model to treat radiative transfer in non-homogeneous and non-isothermal paths and avoid discrepancies resulting from the use of different basical data. For this reason, we do not include the exponential wide band model in the comparisons since Edwards' parameters are not originated from the same spectroscopic data.

The accuracies of the models are compared on the basis of wall radiative fluxes and volumetric radiative power in a planar geometry with prescribed temperature and composition profiles. The medium is an absorbing, emitting but nonscattering H_2O-N_2 mixture and different temperature profiles are tested. Numerical methods for the resolution of the radiative transfer equation (RTE) in association with each radiative property model have been chosen in order to provide a consistant comparison of CPU times required in multi-dimensional geometries. When the model is based on an absorption coefficient formulation (LBL, CK, WSGG), the differential form of the RTE is used and the directional integrations are performed numerically instead of using the semi-analytical formulation with the exponential integral functions since this formulation cannot be generalized to multi-dimensional problems. For the models based on column transmissivities (SNB and CKFG), the integral form of the RTE is used.

The results are discussed from several points of view. The use of a mean transmissivity based model with a deterministic method for the resolution of the RTE resolution requires a noncorrelation approximation to treat reflection at a wall or more generally radiation scattering. The errors due to this approximation reach 15% in the applications considered in this study. Absorption-coefficient based models are more suited to treat problems where reflection and scattering are important. For applications where gas emitted radiation is mostly absorbed by a long cold medium before reaching a wall, only the CKFG model provides accurate wall fluxes. The corresponding computational times are very important but they could be reduced with optimized spectral resolutions and quadratures. The WSGG model is the less expensive one but it yields generally very important and sometimes unpredictable discrepancies. Absorption by gases at a temperature different from the emitting temperature cannot be accurately predicted from this model. Another limitation of this model is that it can only be applied when wall or particle radiative properties are gray. For instance, its extension to the case of selective walls requires the subdivison of the spectrum into wide bands and the use of the WSGG model for each band. Model parameters are then no more universal and should be calculated for each particular application.

THE SPECTRAL LINE WEIGHTED-SUM-OF-GRAY-GASES MODEL--A REVIEW

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ABSTRACT

This paper reviews the development and validation of the Spectral-Line Weighted-Sum-of-Gray-Gases (SLW) model for the prediction of radiation transfer in high temperature gases. The parameters in the model are obtained directly from the line-by-line spectra of the primary radiating species in combustion environments, H_2O and CO_2. The model allows the absorption coefficient to be the basic radiative property rather than a transmissivity or band absorptance *etc.*, and can therefore be used with any arbitrary solution method for the Radiative Transfer Equation (RTE), and for multidimensional situations. The model is based on a novel absorption-line blackbody distribution function, which is generated and fit empirically from detailed spectral line data. The model has been formulated for applications of increasing complexity including isothermal/homogeneous media, non-isothermal/non-homogeneous media, binary gas mixtures, and non-gray boundaries and particulates. Sample problems using the model are compared with spectral line-by-line integrations. Predictions from the model compare well with spectral line-by-line benchmarks.

TR9700103

EFFECTS OF LINE DOPPLER SHIFT ON INFRARED RADIATION IN HIGH VELOCITY FLOWS

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The emission lines of a gaseous medium at a given velocity are shifted by Doppler effect with respect to their initial position. The effect of this line Doppler shift is an increase in the radiative intensity emitted by a gaseous jet and transmitted through gaseous columns at rest. This is expected to occur for instance in applications involving long-range sensing. This increase is significant when the shift is at least of the same order of magnitude as a characteristic mid-height half-width of both emission and transmission profiles of representative lines. This effect has been systematically studied using a line-by-line approach based on the EM2C high temperature data bases related to H_2O and CO_2. Simulations have been carried out in the case of two columns, one at 1000 K and at a given velocity V, the other at 216 K and at rest; both columns are at the same pressure. The line Doppler shift effect is considered for an isolated line, for a narrow band and for a whole absorption band successively. It is shown that for a given isolated line, there are precise optical path conditions for which the Doppler shift effect on transmitted radiative intensity is maximum. Apart from these conditions, the Doppler shift effect decreases quickly. In the case of a narrow-band containing a few well-separated lines, it can be significant but is however about two times less important than in the case of an isolated line. Our simulations show that for a global absorption band (CO_2 near 2.7 and 4.3 μm, H_2O near 2.7 μm), the line Doppler shift can increase the transmitted radiative intensity by up to 15 % for a pressure of 0.1 atm and a velocity V of 2000 m/s. This phenomenon is more important for H_2O than for CO_2 since the absorption lines of H_2O are more separated than those of CO_2. The maximum Doppler shift effect decreases as the spectral band width over which radiative intensities are integrated increases. Indeed, for a wide spectral band and given thermophysical conditions, there are very few lines for which the Doppler shift effect is important. For velocities lower than 1000 m/s and pressures greater than 0.1 atm, the increase in the transmitted intensity is limited to 4 %.

THE ABSORPTION-LINE BLACKBODY DISTRIBUTION FUNCTION AT ELEVATED PRESSURE

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ABSTRACT

The previously published mathematical correlations of the absorption-line blackbody distribution function, central to the spectral-line based weighted-sum-of-gray-gases model (SLW), have been extended to elevated pressures by introducing a dependence on an effective broadening pressure. The distribution function attempts to capture the spectral information of the line-by-line variation in absorption cross-section in an empirical form. Effective pressures ranging from 0.32 to 100 atm This extends accepted previous theoretical approaches to the distribution function. Comparisons between experimentally determined total emissivities and those calculated with the model show good agreement. Very good agreement at elevated pressure between line-by-line benchmarks and model predictions is also demonstrated.

SESSION 6

ATMOSPHERIC AND STELLAR RADIATIVE TRANSFER

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ATMOSPHERIC OPTICS AND RADIATIVE TRANSFER

C. Bohren

Abstract not available

TR9700105

STELLAR WINDS DRIVEN BY RADIATION PRESSURE

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ABSTRACT. The interaction of radiation with matter results in momentum transfer from the radiation field to the intervening medium. The resulting force points in the direction of the net radiation flux and is proportional to both the flux and the optical depth of the medium. In non-astronomical environments, such forces are usually negligible. However, when the luminosity of a star is about 10000 solar luminosities, the radiation pressure force at the top of its atmosphere can become larger than the gravitational force and the outer layers of the star are blown away. A continuous process of such mass-loss results in a stellar wind and an expanding envelope surrounding the star.

We present a detailed, self-consistent model of the radiatively driven winds which couples the radiative transfer and hydrodynamics equations. The circumstellar envelope, which consists of gas and dust, is described as a two-component fluid to account for relative drifts. The radiative transfer equation is treated in the moment form.

Our results show that steady-state outflows driven by radiation pressure on dust grains adequately describe the surroundings of late-type stars. Thanks to scaling properties, both the dynamics and the radiative transfer are fully characterized by τ_F, the flux averaged optical depth of the wind. The region of parameter space where radiation pressure can support a given mass-loss rate is identified, and it shows that radiatively driven winds can explain the highest mass-loss rates observed to date. A new procedure to derive mass-loss rates from the observational data is introduced, and its results agree with other determinations. Theoretical predictions for the dust emission are in good agreement with observations. Observed spectra are associated with different τ_F and various grain materials, and a new method to determine τ_F from infrared observations is presented. We show that analysis of infrared spectral signatures provides constraints on the grains chemical composition and find that, in carbonaceous grains, the abundance of SiC grains is limited to $\leq$ 20–30%. Similarly, in mixtures of astronomical silicate and crystalline olivine, the abundance of olivine is limited to $\leq$ 20–30%.

BROKEN-CLOUD ENHANCEMENT OF SOLAR RADIATION ABSORPTION

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ABSTRACT. A pair of papers recently published in Science have shown there is more absorption of solar radiation than estimated by current atmospheric general circulation models (GCMs), and that the discrepancy is associated with cloudy scenes.

We have devised a simple model showing how fields of broken clouds cause average photon path lengths to be greater than those predicted by homogeneous radiative transfer calculations of cloud/atmosphere ensemble with similar albedos, especially under and within the cloud layer. This one-sided bias is a contribution to the anomalous absorption. This model has been described by us previously and is reviewed here for clarity. We illustrate the model quantitatively with a numerical stochastic radiative transfer calculation. More than half the anomaly is explained, for the parameters used in the numerical example.

INFRARED ASTRONOMICAL SOURCES: CLASSIFICATION BASED ON SCALING PROPERTIES OF THE RADIATIVE TRANSFER PROBLEM

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ABSTRACT. Astronomical objects usually appear as point sources since most observations are incapable of resolving them. Thus the only way to infer the nature of a source is spectral analysis of observed flux. Many objects are embedded in a dusty envelope which scatters, absorbs and re-radiates the radiation emitted by the underlying source. As a result, spectra of these objects are shifted toward the infrared wavelengths.

For dust heated only by the radiation field we show that the resulting spectral shape does not depend on the spatial dimensions of the underlying source and envelope. The only parameters that specify the radiative transfer problem are the overall optical depth and, unlike for plan-parallel geometry, the functional form of the dust spatial distribution. The properties of the central source enter only through its spectral shape and are not important at the infrared wavelengths considered here. Consequently, for a given dust chemical composition, the resulting spectrum is fully determined by the dust spatial distribution and overall optical depth. This conclusion is of great importance since objects of different nature are expected to have different dust spatial distributions, dependent mainly on whether the envelope is collapsing onto or expanding away from the central source. Thus, detailed radiative transfer modeling can provide efficient methods to determine the amount of dust, its chemical composition and the nature of the object which emitted the observed spectrum.

Our models show that observations obtained by the Infrared Astronomical Satellite (IRAS) can indeed be interpreted in terms of the overall optical depth and dust spatial distributions. Preliminary comparison with results obtained for some sources by other methods verify the basic premises and show that reliable classification of all sources observed by IRAS is feasible.

SESSION 7

OPEN FORUM ON RADIATIVE TRANSFER AND ITS APPLICATIONS

CHAIRMAN: M.P. Mengüç
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SESSION 8

OPTICAL AND RADIATIVE PROPERTIES OF SOOT PARTICLES

CHAIRMAN: Y. Kurosaki
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STRUCTURE AND BONDING OF CARBON CLUSTERS AND PARTICLES PRODUCED DURING COMBUSTION

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ABSTRACT. Carbon containing submicronic particles and clusters produced during combustion have relevance for the prediction of radiative heat transfer in combustion systems or at ambient temperature for the thermal balance of the atmosphere. The spectral dispersion of absorption and scattering coefficients of particles from the near u.v. down to the infrared is a necessary input for radiative heat transfer models. The spectroscopic and optical properties are direct expression of the structures and bonding of the particles and clusters, therefore a preliminary discussion of our knowledge on this matter is required. In the last few years great progress has been made in the physical and chemical characterization of carbon containing structures produced at high temperatures; fullerenes, including the "magic bucky ball" C_{60}, have been detected as major percentage components in soot formed by high temperature combustion. On the other side diamond-like films or particles can be easily produced by hydrocarbon plasma assisted pyrolysis or quenched. Bonding of carbon containing structures may range from pure sp^3 states passing through intermediate combination of both typed of bonding, with different degree of medium range spatial organization inside the particles. In addition, the long range organization of the structures, i.e. their typical size and shapes, is determined by the clustering, surface growth and coagulation/agglomeration processes, and exhibits a clear multimodal size/shape distribution functions. Spectroscopic and optical effects like absorption, fluorescence, Raman, and Rayleigh-Lorenz light scattering can "probe", according to the case, short, intermediate and long range organization of nuclei and electrons inside the structures. They also yield information on bonding, cristallinity, and overall size and shapes of carbon containing structures. Illustration of these examples will be discussed from recent spectroscopic work obtained by different groups operating with premixed flames, shock tubes and analogue experiments for interstellar dust research.

TR9700109

PREDICTION OF RADIATIVE ABSORPTION OF SOOT AGGREGATES IN THE RAYLEIGH LIMIT

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ABSTRACT. It is well known that thermal emission from soot particles can constitute the dominant fraction radiative heat transfer from large-scale flames. Typically, the sizes of aggregated soot particles will be considerably smaller than the infrared radiation wavelengths associated with thermal emission in flames. Because of this, the radiative absorption properties of the soot aggregates – which are essential to accurately model radiative transfer in flames – can be predicted using an electrostatics (or Rayleigh limit) analysis. Such an analysis is presented here. In the electrostatics limit the radiative absorption and scattering properties of a particle can be obtained from solution of Laplace's equation for the particle configuration. A general analytical solution of Laplace's equation, based on a coupled spherical harmonics formulation, is developed for multiple sphere configurations that are characteristic of aggregated soot particles. The method enables the determination of the effective polarizability of the soot aggregate, from which the scattering and absorption cross sections of the aggregate can be obtained. Calculations of soot absorption are performed on fractal-like configurations of spheres. The configurations are generated using a pseudo-random algorithm which creates a sequence of sphere positions that exactly satisfy the fractal relationship for prespecified values of fractal dimension and prefactor constant. Results indicate that, first, the independent sphere (or Rayleigh-Gans-Debye) model, in which the aggregate absorption cross section is given as the sum of the primary sphere cross sections, can significantly underpredict the absorption of the aggregate when the real and imaginary parts of the sphere refractive index are large. For refractive index values typical of carbonaceous soot in the IR wavelengths the aggregate absorption cross section can exceed the sum of the sphere cross sections by as much as 100%. Because of the spectral variation of carbonaceous soot refractive index this effect is expected to be most significant in the near to mid IR radiation wavelengths, and can lead to Planck mean absorption coefficients that are on the order of 20–50% greater than those predicted from spherical Rayleigh models at typical combustion temperatures. Secondly, it is shown that the Rayleigh-limit absorption properties of fractal aggregates

scale according to the ratio of the primary sphere radius a_p and the aggregate radius of gyration R_g. This behavior allows the development of a relatively simple formula that predicts Rayleigh–limit aggregate absorption efficiency for arbitrary fractal dimension and number of spheres in the aggregate. Finally, the behavior of aggregate absorption in the resonance region (i.e., comparable aggregate sizes and radiation wavelength), obtained via exact solution of Maxwell's equations for the sphere configuration, is discussed. By normalizing the aggregate absorption efficiency with that obtained in the Rayleigh limit, it is shown that the absorption properties of aggregates having arbitrary size parameters, fractal dimension, and number of spheres can be represented by a single, characteristic size parameter $x_C = x_V(a_p/R_g)^{1/4}$, in which $x_V = 2\pi a_p N_S^{1/3}/\lambda$ is the volume–equivalent size parameter of the aggregate. The curves of normalized aggregate absorption efficiency vs. x_C are shown to be a function solely of primary particle refractive index. Implications of the results on the effects of soot on flame emission and radiative propagation in the atmosphere are discussed.

THE RADIATIVE PROPERTIES OF SOOT AGGLOMERATES: THE MODEL OF THE VIRTUAL REFRACTIVE INDEX AND FIRST-ORDER MULTIPLE SCATTERING

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Investigations on the radiative heat transfer within densely particulate laden combustion systems require knowledge of the electromagnetic cross sections of the combustion aerosols. Commonly, calculations based on the Mie theory for isolated spherical particles of arbitrary size are applied. Assuming isolated spherical particles the Rayleigh approximation is also suitable in performing calculations within the far infrared region of the electromagnetic spectrum.

Numerous experimental investigations on the morphology of flame-generated aerosols, however, showed the presence of agglomerates formed by up to several hundred spherical primary particles arranged in fractal structures. Thus, the use of the Mie theory as well as the Rayleigh approximation is *a priori* rather questionable as the electromagnetic interaction within the agglomerate must be taken into account. Many efforts, therefore, have been made during the recent years in order to describe the optical cross sections of agglomerated soot particles.

Most of the methods published are limited to primary particles within the Rayleigh limit. Thus, uncertainties are inherent in utilizing these methods calculating the radiative transfer within high temperature flames with an important amount of thermal radiation in the near infrared or even visible wavelengths. The knowledge of the optical cross sections of real combustion aerosols is also important in optical aerosol characterization where the application of visible wavelength has to be preferred due to a minimization of disturbance caused by thermal radiation. Consequently, a method is required which provides the possibility to describe the electromagnetic interaction of nearby spherical particles of arbitrary size.

The electromagnetic interaction may be considered as multiple scattering within an agglomerate. Thus, in this presentation at first a qualitative analysis of the multiple scattering effects within an agglomerate is performed. First-order multiple scattering is found to provide a sufficient approximation to the particle interaction as, due to the strong absorption of the particles under consideration, the intensity of the scattered light decreases rapidly with increasing multiple scattering order. Furthermore, if large agglomerates of fractal structure are considered arbitrary phase shifts of the multiple scattered light in higher orders are found, thus leading to extinguishing scattered electric fields.

With knowledge of the first-order multiple scattering approximation the remaining task is to quantify the secondary scattering. The problem arising here is the anharmonic behaviour of the scattered electromagnetic field in space within the near field zone. Thus, a major condition for the application of the Mie theory is not satisfied. In order to enable a solution, though, a transformation is found providing a formal description of the electromagnetic field scattered once as an electromagnetic oscillation harmonic in space and time. Subsequently, introducing the so-called virtual refractive index, the secondary scattering can be described by a modified Mie formulation. The virtual refractive index enables the calculation of the secondary scattering for spheres of arbitrary size even at the closest particle distance possible. Due to the simplicity of the model presented, it can be applied to agglomerate geometries as complex as real combustion aerosols with little numerical expense.

By means of this model a general formula for the light extinction caused by soot particles agglomerated in fractal structures was found. Results were compared with those available in literature for small primary particles within the Rayleigh limit as well as with results for the light scattered by a very special agglomerate geometry consisting of larger primary particles. In all cases an excellent agreement was found proving the validity of the model presented. Furthermore, extinction cross sections were calculated for agglomerates consisting of primary particles with the diameter up to the magnitude of the light wavelength. Although no reference data were available here, the results were throughout consistent.

Summarizing, the model of the virtual refractive index and first-order multiple scattering can be viewed to as a suitable tool in calculating the radiative properties of soot agglomerates.

TR9700111

ON MEASURING THE MUELLER MATRIX ELEMENTS OF SOOT AGGLOMERATES

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Understanding the formation of soot particles and agglomerates in flames is very important in order to design more efficient, economical and environmentally friendly combustion systems. The scattering characteristics of soot particles and agglomerates reveal more about their size and can be used to determine their volume fraction distribution in flames. In particular, the angular dependence of scattering of various states of polarized light from small particles and agglomerates can yield much information about the nature of the scatterers. In this paper we make use of this concept to propose an experimental procedure which can be used to obtain accurate information about the physical properties of the soot agglomerates.

The intensity and polarization of a beam of light can be completely specified by the four-element Stokes vector. The interaction of an optical device with a beam of light can be described as a transformation of an incident Stokes vector $[K_i]$ into an emerging Stokes vector $[K_o]$

$$[K_o] = [S] \cdot [K_i]$$

where $[S]$ is the 4×4 matrix known as the Mueller or scattering matrix. It is a characteristic of the optical device or the medium causing the transformation.

Recently, Manickavasagam and Mengüç (1995) discussed the variations of the Mueller matrix elements of different soot agglomerates and showed how these can be used to recover the agglomerate size, structure and volume fraction in flames. Here, we propose an optical setup as shown in Fig.1 to measure the Mueller matrix elements for particles in flames.

This setup uses a laser along with several retarders (half and quarter wave plates) and polarizers. The orientation of the optical components with respect to the optical axis is varied several times and the scattered intensity distribution is recorded each time. This leads to a set of linear equations from which the Mueller matrix elements can be easily recovered. Even though this method uses subtractive techniques to obtain the six elements, the accuracy is not affected because the elements to be recovered appear as significant differences between large quantities.

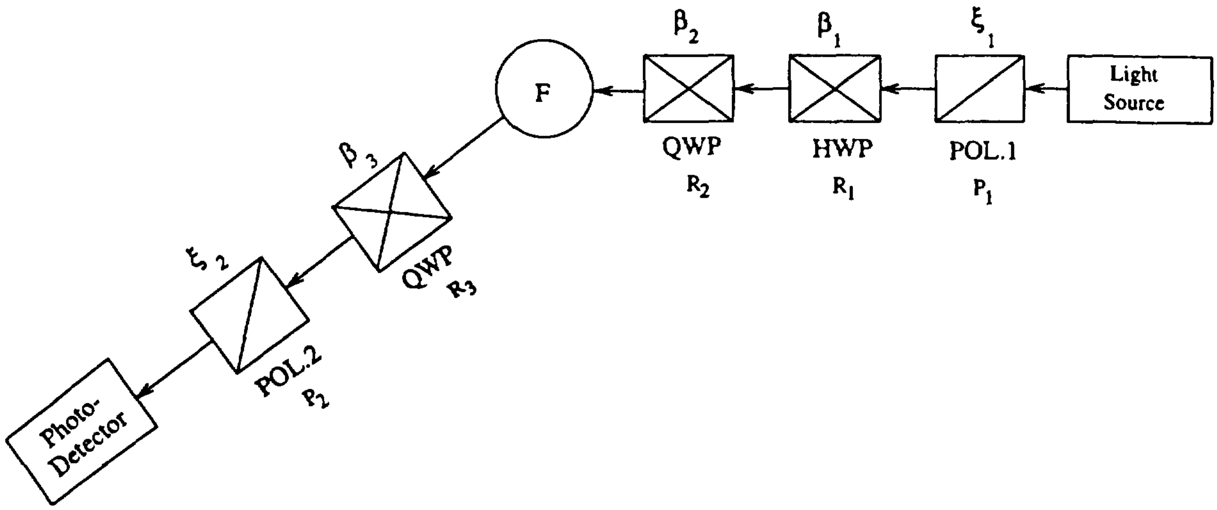

Figure 1. Schematic of the Experimental Setup; POL: Polarizer, HWP: Half wave plate, QWP: Quarter wave plate, F: Flame

The second part of the paper presents the results of a sensitivity analysis performed to determine the optimum set of combinations of the optical components so that the desired Mueller matrix elements of soot agglomerates can be recovered accurately. For this, theoretical results for the matrix elements of soot agglomerates are taken from the *AGGLOME* algorithm.[1] It is found that the most important parameter that affects the accuracy of the recovered matrix elements is the *condition number* (CN) of the coefficient matrix in the linear system of equations. If the CN is large, then the Mueller matrix elements determined from experiments would not be reliable. However, by using a proper combination of the optical components, one can reduce the CN to be less than 10. In this case, it is shown that even if there is $\pm 7.5\%$ error in measured intensities, the recovered S_{11} and S_{12} elements are virtually identical to their true values. These S_{ij} elements could be used in an inverse algorithm to identify the size of soot monomers and agglomerates in flames.

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[1]Manickavasagam, S., Mengüç, M.P., (1995), "Mueller matrix elements of fractal-like soot agglomerates", *Applied Optics* (submitted for publication).

SESSION 9

PARTICLES, FIBRES, THERMOPHORESIS, AND WAVES

CHAIRMAN: D. Mackowski
Auburn University
Auburn, AL, U.S.A.

THE RANGE OF VALIDITY OF THE RAYLEIGH-DEBYE-GANS/FRACTAL-AGGREGATE THEORY FOR COMPUTING THE OPTICAL PROPERTIES OF SOOT

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ABSTRACT. The absorption and scattering properties of soot are needed both to predict the continuum radiation properties of soot and to interpret nonintrusive optical measurements to find soot concentrations and structure. This is a challenging problem because soot consists of small primary particles that combine into branched aggregates that exhibit neither simple Rayleigh, nor Mie scattering behavior.

Recently a potentially useful approximate theory for soot optical properties (denoted RDG-FA theory in the following) has been developed based on the Rayleigh-Debye-Gans (RDG) scattering approximation while assuming that soot aggregates are mass-fractal objects. Measurements of both soot structure and scattering properties for soot aggregates found in flame environments have exhibit good agreement between RDG-FA predictions based on the structure measurements, and the scattering measurements[1,2]. Unfortunately, these soot populations involved relatively large soot aggregates so that it was not possible to adequately test RDG-FA theory in the small angle (Guinier) regime where the use of the RDG scattering approximation is least reliable.

In the present study the range of validity of the RDG-FA theory for computing the optical properties of soot aggregates is investigated. RDG-FA was evaluated by more exact predictions from the solution of the volume integral equation formulation of the governing equations, based on the ICP algorithm of Iskander et al[3]. Numerical simulations were used to construct statistically-significant populations of soot aggregates having appropriate fractal properties, prescribed numbers of primary particles per aggregate, N, and primary particle optical size parameters, x_p. Error contour maps were produced for the total scattering and absorption cross sections as well as differential scattering cross sections for different scattering angles along the Guinier regime. Parameters covered were as follows: number of primary particles within an aggregate up to 256; primary particle size parameter between 0.1 and 1.0 and soot complex refractive index modulus, $|m-1|$, between 0.1 and 1.

In addition, the effects of polydisperse soot aggregate populations and polydisperse soot primary particle size parameter within an aggregate were studied. For the polydisperse aggregate population study the numbers of primary particles per aggregate were chosen to match a log-normal size distribution function with mean values and standard deviations according to experimental data presented by Köylü and Faeth[4]. Primary particle diameter within an aggregate were randomly chosen while satisfying a normal size distribution function with mean values and standard deviations typical of soot aggregates found in the fuel rich and lean regions of laminar and turbulent diffusion flames[4].

Specific ranges of aggregate properties for the present study were as follows: primary particle mean optical size parameter between 0.1 and 0.3 (standard deviation up to 25%), mean number of primary particles per aggregate up to 256, log-normal standard deviation of aggregate size distribution between 1 and 2, mean fractal dimension of 1.75 and refractive indices typical of soot.

The following main conclusion was obtained: while in the large angle (power-law) regime results seem to be independent of polydisperse soot aggregate populations and polydisperse primary particle size parameter, in the Guinier regime a strong influence of these effects was noticed.

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TR9700113

RADIATION TRANSFER IN FIBROUS MEDIA WITH LARGE SIZE PARAMETER

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This paper numerically investigates radiation transfer in fibrous media with a large size parameter using a pseudo-continuous model. Fibrous media have recently been applied for use in a radiation burner [1] and solar energy collector [2] due to their ability to convert energy between thermal radiation and gas enthalpy. In such energy conversion systems, since radiation is emitted from high-temperature sources, its wavelength λ is usually less than the medium's fiber diameter d. Thus, evaluation of the radiation transfer in fibrous media having a large size parameter α (= $\pi d/\lambda$) is essential to improve system performance.

Such radiation transfer is dependent on the fiber's optical characteristics, which are characterized by the material's complex refractive index and its size parameter, as well as the orientation of the fiber, and therefore, to adequately evaluate it, a model is required to establish the relationship between the optical characteristics and fiber orientation.

Towards this end, several pseudo-continuous models [3]–[6] have been developed to clarify the effects of optical characteristics and orientation on the radiation transfer, yet they have not been applied to media with a size parameter greater than 10, *i.e.*, these media have only been studied to evaluate their thermal insulation characteristics at comparatively low-temperature radiation transfer conditions. In addition, the following also causes the lack of the study for radiation transfer in fibrous media with a large size parameter.

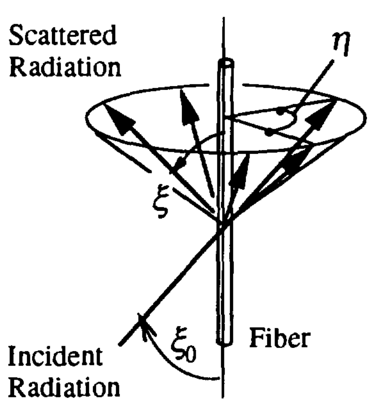

Figure 1 Scattering by a single fiber

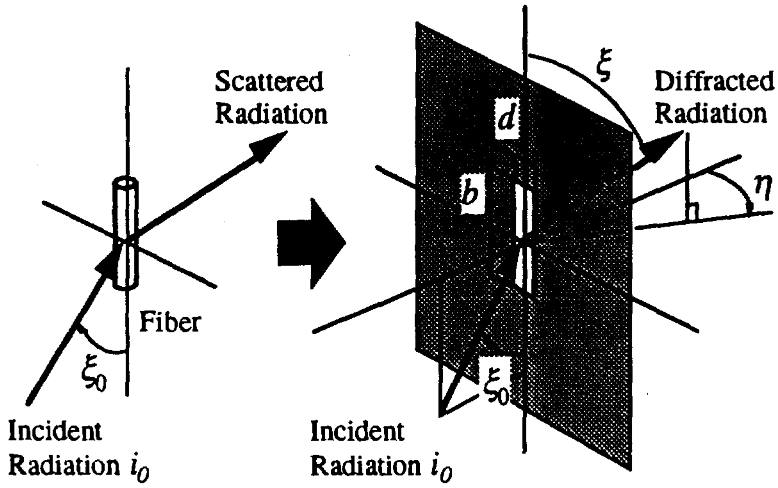

Figure 2 Employed rectangular aperture model for representing diffraction in a fiber

Figure 1 schematically shows how an infinitely long fiber scatters radiation when it is irradiated by collimated radiation, where most is scattered along the surface of a cone having a cone angle of $2\xi_0$ [7, 8]. Such scattering can be characterized by the optical characteristics of a single fiber, namely, its scattering and extinction efficiencies. It is difficult to use conventional methods to determine the optical characteristics of a single fiber having a large size parameter.

In this study, we derive an approximation method for estimating this optical characteristics of a single fiber with such a size parameter by considering (i) the Fraunhofer diffraction of a rectangular aperture to represent diffraction in a fiber (Fig. 2) and (ii) the specular reflection off the surface of a fiber, with the effects of available size parameters for fibers being subsequently clarified by comparing these approximated optical characteristics with exact ones.

In addition, we also use the resultant optical characteristics to estimate the radiative properties of and radiation transfer in two types of planar fibrous media having a typical orientations. Based on our results which cover a wide range of size parameters, we subsequently discuss the effects of the complex refractive index and fiber orientation on the radiative properties and radiation transfer associated with a single fiber.

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TR9700114

THE MIE THEORY ANALYSIS OF COMPARABLY DENSE DISPERSE SYSTEMS

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ABSTRACT: In this paper, high-density disperse systems of randomly placed particles are considered. Applicability of the Mie theory and the radiation transfer theory for these systems is not obvious due to small distances between particles in comparison with the radiation wavelength. Solutions of the following problems are presented:

1) Microwave emissivity of a foam on the water surface both for the emulsive monolayer and the honeycomb structure including the spectral range, in which the wavelength is greater than the foam layer thickness.

2) Absorption and scattering of microwave radiation by metal powder in dielectric at the wavelength much greater than distances between particles.

3) Infrared radiative properties of the quartz fibrous material with numerous contacts between fibers. A comparison of the calculations with the experimental data provides a way of estimating the range in which one may use an assumption that effects of large particle concentration are small. The following results are obtained:

- A microwave thermal radiation of a foam on the water surface may be treated as that of rarefied disperse system of water bubbles. Calculations showed that individual particles are near to the Rayleigh range due to very small thickness of the water shell. A good agreement with the experimental data on spectral emissivity in the wavelength range from 2.6 *mm* to 80*mm* argues for an applicability of the theoretical model without taking into account any collective effects. This conclusion does not hold for observations at small angles to an exposed surface.

- It has been found that the microwave properties of spherical aluminum particles of radius from 1 to 100 μm in the spectral range from 1 to 100 *mm* are specified by the magnetic dipole scattering. Simple analytical expressions for disperse system characteristics by taking into account two first partial waves amplitudes in the Mie solution are derived. It was shown that there is a sharp decrease of the specific absorption coefficient in the centimeter range with the decrease of the particle radius when it is less than 2 μm. A comparison with the experimental data for a disperse system with an

average particle radius about 7 μm at the wavelength $45 mm$ confirms an applicability of the theoretical model up to particle concentration $100 kg/m^3$.

- Infrared radiative properties of the quartz fibrous material with randomly oriented fibers are calculated by use of the scattering theory for infinite cylinders at oblique incidence of the radiation. A comparison of the calculated values of the radiation diffusion coefficient with the experimental data in the semitransparency region shows that a nonsignificant discrepancy in the visible range may be explaned by a more intensive scattering by bends and seals of fibers. One can obtain an evaluation of this effect by addition of small amount of spherical particles of radius equal to that of the most thin fibers. Collective effects, which are expected first of all in the long-wavelength region, do not observed even for the fibrous material of comparably large density $144 kg/m^3$. An additional verification of the theoretical model is obtained by comparison with the spectral measurements of the optical thickness for samples of fiberglass insulation of density $86 kg/m^3$.

THERMOPHORESIS OF RADIATING AEROSOLS

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ABSTRACT: The interaction of radiation and thermophoresis of radiating aerosols is discussed both in external laminar boundary-layer flow over a cold surface and in the thermally developing laminar flow in a parallel–plate channel. In both cases, the fluid is a radiatively nonparticipating constant-property gas containing emitting, absorbing and isotropically scattering gray aerosol particles, with their absorption and scattering coefficients being proportional to the local concentration of particles in the mixture. Various results are presented to illustrate the effects of the parameters of the problems on the temperature and aerosol concentration distributions, as well as on the heat and particle flux to the plate in the external flow case.

In the channel flow case various results are also presented for the particle deposition efficiency along the channel when the walls are cold and on the development of the particle–free zone along the walls when they are hot.

RADIATIVE-CONDUCTIVE TEMPERATURE WAVES IN HALF-INFINITE SEMI-TRANSPARENT MEDIA

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ABSTRACT. The interaction between radiative and conductive heat transfer is analyzed in semi-transparent gray non-scattering media under periodical external heat action. Two dimensionless parameters are proposed for classification of radiative-conductive temperature waves. Singular eigenfunction expansion method is used to obtain an exact quasi-steady solution to the system of radiative transport and energy equations. Various boundary conditions are considered. The problem is reduced to a singular integral equation of the Cauchy type. Exact analytical solution is written out in a closed analytical form in case of simplest boundary condition for radiative transport equation by Muskhelishvili's theory for singular integral equations. Regularization of the singular integral equation is proposed in case of scattered and reflected boundary. Numerical technique is developed for solving the regular equation.

New effect of temperature wave bifurcation is briefly discussed. The bifurcation is the appearance or disappearance of second temperature wave while the frequency of external heat action or the mean temperature of the medium are changing slowly. The bifurcation does not result from instabilities and nonlinearities, but arises from the competition between radiative and conductive heat transfer. Effect of different type of reflection from the boundary on temperature wave propagation is numerically examined.

Applications of the results to nondestructive absorption coefficient measurements by thermal wave techniques are considered. It is shown that there exists optimal value of absorption coefficient, which maximizes contribution of radiation to the combined heat transfer while other properties of the medium and parameters of the external heat action are fixed. Dimensionless estimation of contribution of radiative heat transfer relative to conductive heat transfer is proposed. The estimation is useful for arbitrary nongray medium with unknown optical properties.

SESSION 10

INVERSE RADIATION PROBLEMS I

CHAIRMAN: M. Lallemand
ENSMA
Futuroscope, France

INVERSE PROBLEMS OF RADIATIVE TRANSFER IN ABSORBING, EMITTING AND SCATTERING MEDIA

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This work reviews and summarizes the current state-of-the-art techniques utilizing the Levenberg-Marquardt method, conjugate gradient method and a combination of both for solving inverse problems in radiative transfer. Illustrations are given in order to show the utility of each, as applied to function, parameter and property identification. We also examine the effects of measurement errors on the accuracy of estimations by inverse analysis.

In high temperature systems, radiative transfer is the fundamental mode of heat transfer. In most engineering applications the properties, the boundary conditions and the source terms in the medium are assumed to be known and the radiation flux or intensities are calculated. Such problems are referred to as the *direct problem*. However, if one or more of the properties or source term is unknown and measured radiation intensities are available, an *inverse* solution technique can be formulated in order to estimate the unknown quantity. This paper is intended to give an overview of the Levenberg-Marquardt method, conjugate gradient method and a combination of both in the solution of inverse problems of radiation transfer in participating media.

Recently, several inverse problem techniques that have come to the forefront in the radiative transfer field have their beginning in the solution of inverse problems of heat conduction. They include, among others, the conjugate gradient, Levenberg-Marquardt methods, a combination of the previous two and the Monte Carlo technique. These algorithms have been applied in such problems for the estimation of source terms and boundary conditions, properties, scattering phase function and simultaneous radiation and conduction problems. In this paper we will focus on the conjugate gradient and Levenberg-Marquardt methods for parameter and function estimation.

INVERSE PROBLEM TECHNIQUES

Several methods are currently being applied for solving the inverse radiation problem. Each method is best applied to a particular type of inverse problem as discussed below.

The Levenberg-Marquardt Method This technique is used solely for parameter estimation. It is a combination of a steepest descent and Newton's methods for minimization type problems. The method requires the minimization of the least squares norm functional and the solution of the sensitivity problem. The number of parameters to be solved for should not be too large as instabilities may emerge in the iteration process. The method is accurate, can handle nonlinear parameter identification, but generally needs a good starting estimate of the unknown parameters in order to achieve convergence.

The conjugate gradient method This method also uses the least squares norm and requires sensitivity coefficients as was described in the Levenberg-Marquardt technique. The conjugate gradient method can be applied to both parameter and function estimation problems. When the problem involves parameter estimation, we need only the sensitivity problem. When a function is to be estimated, however, an adjoint variable with a gradient equation must also be used in the analysis. The technique allows for initial estimates of unknown parameters or functions far from the final converged results.

The combined method For parameter estimation problems, the Levenberg-Marquardt and conjugate gradient methods may be combined in situations where a satisfactory initial guess value can not be found with the Levenberg-Marquardt method. The new algorithm uses the conjugate gradient method of solution in order to provide an initial estimate for use as the initial guess for the Levenberg-Marquardt method. The only drawback may be the extra time involved for programming.

EXAMPLE PROBLEMS

Problem #1 *Conjugate Gradient Method for Parameter Identification*
We begin with a problem that will utilize the conjugate gradient method for parameter identification for an absorbing, emitting and isotropically scattering plane parallel medium. The problem consists of the equation of transfer for isotropic scattering. The boundary conditions are with one boundary reflecting and the other transparent. The objective of the analysis is to estimate the unknown coefficients a_n of a volumetric source term represented as a polynomial and unknown reflectivity of the boundary surface from measured exit intensities.

Problem #2 *Combined Levenberg-Marquardt and Conjugate Gradient Method (parameter)*
This problem is concerned with the estimation of a temperature source term represented as a polynomial in an absorbing, emitting and isotropically scattering sphere using a combined conjugate gradient and Levenberg-Marquardt method in the sense that the converged solution of the conjugate gradient method provides the initial guess for the Levenberg-Marquardt method which is then iterated until the final converged solution is obtained.

Problem #3 *Conjugate Gradient Method as Function Estimation*
This problem illustrates the estimation of an unknown volumetric source term represented in functional form. The conjugate gradient method with adjoint equation is best suited for function estimation. We apply this method in order to determine an unknown temperature source term in an absorbing, emitting and anisotropically-scattering plane-parallel medium using measured exit radiation intensities.

TR9700118

INVERSE RADIATIVE ANALYSES TO DETERMINE RADIATIVE PROPERTIES USING TEMPERATURE WAVE METHOD

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ABSTRACT. A universal technique based on the temperature wave method is described for nondestructive determining the spectral radiative properties at high temperatures. The temperature wave method requires pulse-periodic laser heating of a sample, and the measurements of thermal radiation on examined wavelengths, and the digital spectral analysis of laser power indicator and radiometer signals. The simplest case of non-scattering half-infinite medium with translucent mirror boundary and with small impact of radiative heat transfer on temperature waves is considered in detail as an example. Thermal diffusivity of the sample is taken as known. The absorption coefficient on wavelength of thermal emission as well as on wavelength of excitation are to be determined from the experiment.

The sensitivity of the inverse problem to experimental errors is numerically examined without its full solving. The inverse problem is based on the approximation of the measured frequency response function of the sample by the theoretical one on several initial harmonics of basic frequency of the laser heat action. The approximation is carried out using the non-linear least squares method. The random error theory of the inverse problem is a combination of classical random process theory and well-known theory of the least square method. The sensitivity is calculated using the singular value decomposition of the design matrix. The design matrix is calculated by numerical derivation of theoretical frequency response function of the sample with respect to determined parameters.

Optimal parameters of the pulse-periodic laser heating are evaluated. Sensitivities of several kinds of the temperature waves method are compared. The method is contrasted with known techniques of photo-thermal radiometry.

TR9700119

INVERSE RADIATIVE HEAT TRANSFER TECHNIQUE FOR HEAT FLUX RESTORATION USING OPTIMAL WIENER FILTRATION

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The spatial distribution of energy on the treated surface should be known for better control in many applications in laser and solar technologies and material science. The increasing heat losses due to radiation, convection and conduction may change or reduce thermal efficiency of material processing. This paper presents a new technique for restoration of heat flux' distribution for the sheet material using temperature measurements with random errors . Let us consider the thin wall with radiative heat flux distributed on the external side and cooling by convection on the internal side. Due to finite thickness of the wall conduction redistributes heat fluxes and the direct application of the Fourier law to estimation of heat fluxes on the surfaces is impossible.
The asymptotic methods have been used to reduce 3D problem into 2D formulation for thin wall and the zero approximation of 3D transient conduction equation can be written in form

$$\frac{\partial \mathbf{T}}{\partial t} = \frac{\partial^2 \mathbf{T}}{\partial \mathbf{x}^2} + \frac{\partial^2 \mathbf{T}}{\partial \mathbf{y}^2} + \mathbf{q}(\mathbf{x},\mathbf{y}) \qquad (1)$$

where **x, y** - coordinates on the wall, **k**- thermal conductivity, **d**- thickness of the wall, with right side term **q** containing difference of heat fluxes on external and internal sides of wall. The heat flux restoration algorithm is based on the spectral analysis of 2-D discrete Laplacian operator with data filtration in frequency domain using optimal Wiener filtration and quasi-Wiener filtration.
The proposed algorithm of radiative heat flux restoration can be described by following step-by-step instruction:

- The initial measured temperature data $\mathbf{T}^*_{i,j}$ are converted into Fourier components $\tilde{\mathbf{T}}^*_{n,m}$ by standard 2-D sine FFT.
- The Fourier components $\tilde{\mathbf{T}}^*_{n,m}$ are filtered by an appropriate 2-D low pass Wiener filter with frequency response $\mathbf{wf}_{\mathbf{n,m}}$
- Calculate the corrected values of heat flux' harmonics $\tilde{\mathbf{q}}^{*F}_{n,m}$ by:

  $$\tilde{\mathbf{q}}_{n,m} = -4(\mathbf{N}-1)^2(\sin^2(\pi n/\mathbf{N}) + \sin^2(\pi m/\mathbf{N}))\tilde{\mathbf{T}}_{n,m}$$

- The recovered heat flux distribution $\mathbf{q}^{*F}_{i,j}$ is obtained by inverse 2-D sine FFT of the corrected harmonics $\tilde{\mathbf{q}}^{*F}_{n,m}$.

Estimations of radiative heat fluxes have been obtained for different wall thickness of the sensor and different signal to noise ration in temperature data. To study the effect of noises on the accuracy of the proposed heat flux restoration technique, the series of numerical experiments have been carried out. The initial temperature data and results of restoration are presented in Fig. 1-2. The accuracy of heat flux restoration technique has been studied both for Wiener and quasi-Wiener filtration and the simple practical criterion of selection of a regularization parameter has been proposed.
The reported results demonstrate the main features of new heat flux estimation technique; its simplicity, high rate of processing, stability and adequate accuracy and spatial resolution. The

developed algorithms can be used for study of interaction of an incident radiative heat fluxes with the thin walls and creates new opportunities for radiative heat transfer measurements.

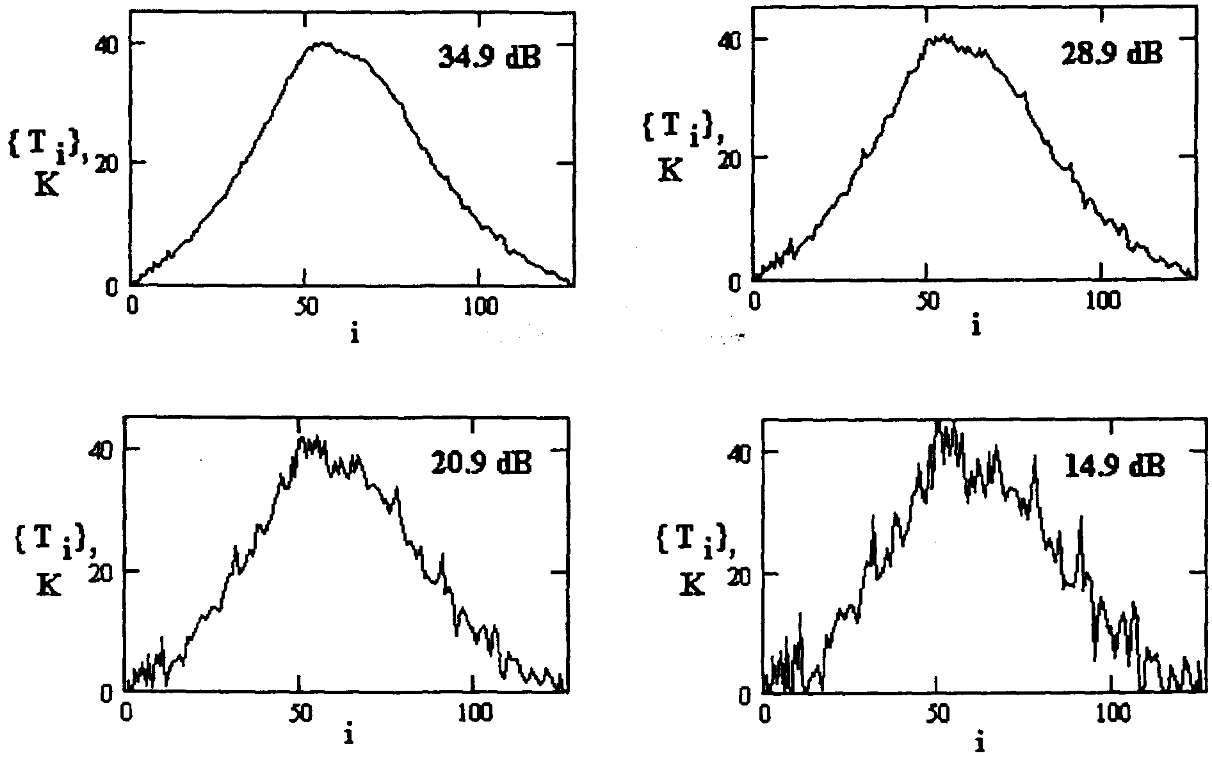

Figure 1. Temperature distributions measured with errors at different averaged SNR.

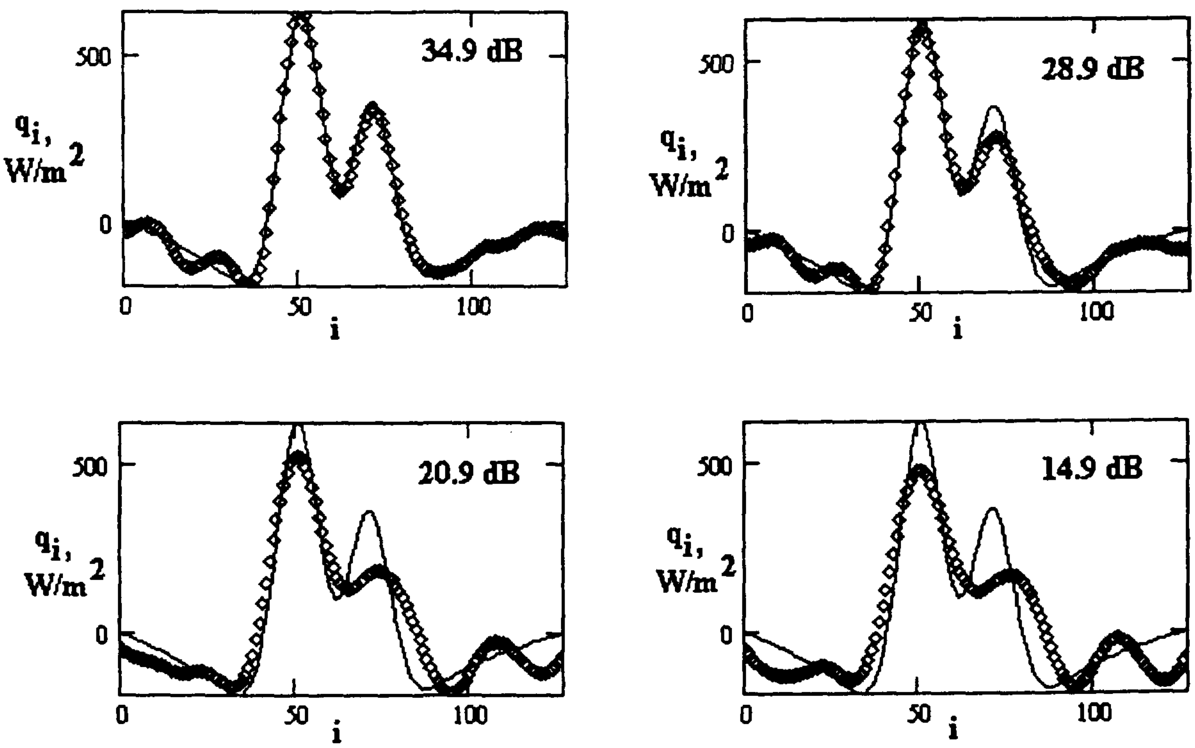

Figure 2. Heat flux restoration with Wiener filtration for different averaged SNR
points - restored data, line - exact distribution

AN INVERSION TECHNIQUE FOR OPTICAL COMPUTED TOMOGRAPHY

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TR9700120

1. INTRODUCTION

The development of non invasive medical imaging techniques over the last several decades has greatly increased the ability of physicians to detect and diagnose disease and injury. While techniques such as x-ray computed tomography, magnetic resonance imaging, ultrasonic imaging, and positron emission tomography provide detailed images of biological structures, it is not possible to use these techniques to continuously monitor tissue or to determine the functional state of tissues. Optical computed tomography is an imaging modality which uses red and near infrared light to probe biological tissues. The goal of optical computed tomography is to obtain a mapping of the absorption coefficient throughout the tissue. Since the absorption spectra of oxygen carrying chromophores depend on their oxygenation state, an image which contains information regarding both the structure and functional status of tissue can be obtained by localizing variations in the absorption coefficient. In addition, biological tissue can tolerate large doses of red and near infrared light, so it is possible to continuously monitor tissue using optical computed tomography. In this paper we briefly describe a method of obtaining mappings of the absorption coefficient of a medium from measurements of the flux on the boundary.

2. EXAMPLE PROBLEM

Light propagation in highly scattering, weakly absorbing medium such as biological tissue is often described using the diffusion or P1 approximation to the radiative transfer equation. The time independent photon diffusion equation is given by

$$\nabla \cdot \kappa \nabla \Phi = \mu_a \Phi - q \tag{1}$$

where κ is the diffusion coefficient, Φ is the photon fluence rate, μ_a is the absorption coefficient and q is the source term. In the derivation of Eq. (1), we were required to assume the source was isotropic. Assuming no reflections at the boundary, the boundary condition for Eq. (1) is given by

$$-\hat{n} \cdot \kappa \nabla \Phi = \frac{\Phi}{2} \tag{2}$$

In order to demonstrate the method of obtaining mappings of the absorption coefficient, we consider the problem illustrated in Fig. 1. The scattering coefficient has a constant value of 10 mm^{-1} throughout the medium and that the absorption coefficient is zero everywhere except the darkened region, where it is 1.0 mm^{-1}. The asymmetry parameter is 0.9 throughout the medium. The diameter of the region shown in is 20 mm. A finite element method and the grid of 800 triangular element is used to solve the forward problem.

3. INVERSION PROCESS

Using the finite element model we obtain the following relationship between the absorption coefficient of each element and each of the measurements, M_p. The measurement set consists of 30 measurements of the flux on the boundary at the nodal points between 90° and 153° and between 207° and 270°.

$$J_{pq}\left[\mu_{a_q}^{i+1} - \mu_{a_q}^{i}\right] = M_p - \Phi_p\left(\mu_a^i\right) \tag{3}$$

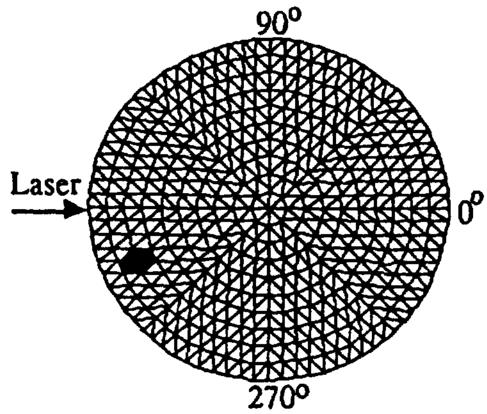

Figure 1. Finite Element Model

In Eq. (3) μ_a^i is the absorption coefficient from the previous iteration and the Jacobian matrix, J, represents the sensitivity of the p^{th} measurement to changes in the absorption coefficient of the q^{th} element. Assuming that the absorption coefficient is initially zero everywhere, we obtain successive approximations by inverting Eq. (3) until convergence is obtained. However, since the number of elements is much larger than the number of measurements, Eq. (3) represents a highly underdetermined system of equations if we vary the μ_a of every element. We overcome the underdetermined nature of the problem by grouping the elements into blocks and varying the absorption coefficient of each element in a block by the same amount. Unfortunately this process also greatly reduces the resolution of the mapping. We are able to increase the resolution of the mapping by using what we call the zooming method. In the zooming method we initially group all the elements into large blocks and obtain a low resolution mapping. We then concentrate the blocks in regions where inhomogeneities appear to be present, hold the absorption coefficient constant outside the region of interest, and repeat the solution process. Equation (3) is inverted using the singular value decomposition of the Jacobian matrix.

4. RESULTS

Figure 2 shows how resolution of the absorption coefficient mapping is improved by using the zooming method. The mapping on the left hand side was obtained when all the elements were grouped into 36 blocks which contain between 16 and 27 elements each. The mapping in the middle was obtained using 30 blocks containing 2 or 3 elements each. The mapping on the right hand side was obtained using 21 blocks which contain only one element each.

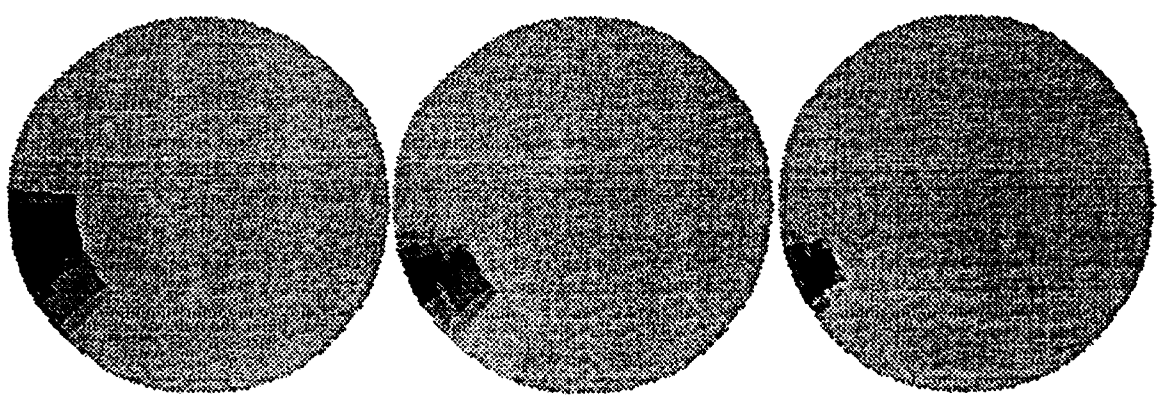

Figure 2. Absorption Coefficient Mappings

SESSION 11

INVERSE RADIATION PROBLEMS II

CHAIRMAN: B. Webb
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TR9700121

INVERSE DESIGN OF RADIATING ENCLOSURES WITH AN ISOTHERMAL PARTICIPATING MEDIUM

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ABSTRACT. Standard analysis of radiative transfer in enclosures with participating media defines a geometry and a specified temperature or energy flux distribution on each surface. The temperature or temperature distribution in the participating medium within the enclosure may also be given. Unknown temperatures and fluxes are then computed. Here, an inverse design procedure is described for radiating enclosures containing an isothermal participating medium. In inverse design, both a temperature and heat flux distribution are given for one enclosure surface (the "design" surface), as would be the case for heat treating furnaces and applications where conditions are required on a particular surface to meet process needs. On one surface of the enclosure, no conditions are imposed; these are then determined from the conditions required on the design surface. The inverse problem requires solving a Fredholm equation of the first kind, which is notoriously ill-conditioned. Description and examples are given of one useful technique.

Solutions are shown for the necessary emissive power distribution on an enclosure surface that will provide a specified temperature and heat flux distribution on another enclosure surface. Effects of the temperature and absorption coefficient of the medium within the enclosure are shown, as are the effects of enclosure aspect ratio and surface properties.

The methods for ascertaining the accuracy and approach to oscillatory solutions inherent in this type of problem are discussed, and the behavior

of the singular values is shown to be a useful tool for reducing the numerical labor involved in the solution.

Some useful solutions are presented that could not be generated by the usual radiative analysis techniques without multiple iterative solutions of the radiative energy equations.

It is argued that inverse solutions present a very useful tool for the thermal analyst, particularly for problems where radiative transfer is a dominant energy transfer mode.

TR9700122

Solution of the Inverse Radiative Load Problems by the Singular Value Decomposition

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A method is developed to solve inverse radiative load problems. The method estimates the heat load distribution and temperature profile within gas region from the values of wall temperature and heat flux distributions, while the shape of the analytical domain and the profile of the optical property values within the system are given. The method can treat arbitrarily shaped multi-dimensional systems with mass flow. In the method, the system is divided into many gas and wall elements, and the radiative heat exchange between each element is calculated by using the Monte Carlo method. By using the results and the mass-flow distributions, the energy equations for each elements are expressed by a matrix form. When the values of the heat-load distribution within the gas region and temperature profile along the wall are given, a set of the matrix equations can easily be solved to obtain the profiles of the gas temperature and wall-heat flux. This is called as forward problem. To obtain the heat-load distribution from the profiles of the temperature and heat flux along the wall: inverse radiative load problem, the matrix which relates the gas temperature to the wall-heat flux should be converted into the inverse form. Due to the ill-posedness of inverse problems, the matrix inversion is usually difficult by using ordinary methods and/or obtained inverse matrix gives very fluctuating results. In the present study, the inverse matrix is obtained by singular value decomposition method.

To check the validity of the method, a forward problem is solved by giving an arbitrarily distributed heat load within a square gray-gas region of 10m x 10m surrounded by gray walls with a temperature of 300K to obtain the corresponding wall-heat-flux distribution. Then, the inverse problem is solved by using the present method by giving the resulting wall-heat flux as the input, and the heat-load distribution within the gas region is estimated. The heat-load distribution obtained from the inverse problem fits very well with those given to the forward problem, which shows the validity of the present method for solving radiative heat-load problems.

By using the method, the radiative heat-load distribution within gas region satisfying the constant heat-flux condition along the wall is also obtained when the condition number of the matrix is reduced to an appropriate lower value by setting some singular values to be 0. The wall-heat flux obtained by using forward problem by giving the resulting heat-load distribution is almost constant with only 1% fluctuations.

The present method can be used not only to estimate the heat-load distribution within furnaces, but also be applied to the problems to decide an optimum burner arrangement within furnaces satisfying prescribed heat-flux profiles.

TR9700123

RETRIEVAL OF ABSORPTION AND TEMPERATURE PROFILES IN PREMIXTED FLAME BY INVERSE RADIATIVE METHODS

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ABSTRACT. Spectral absorption and temperature profiles in a cross section of a premixted propane-air flame have been carried out by inversion of the radiative transfer equation (RTE) from simultaneous directional transmission and emission measurements.
The central element of the experimental setup is a Fourier Transform Infrared Spectrometer working at 4 cm^{-1} resolution. In a given optical line of sight of prescribed optical extention it receives selected angular radiation coming up either from an external source crossing through the flame or from the emission of the flame itself. A black body at 1200K allowed the intenity calibration. The propane-air flame is produced by an axisymmetric burner in which the gases are mixted in a tranquilizer and homogeneizer chamber. Its richness is fixed close to one.

In a given cross section, perpendicular to the symmetry axis of the flame (of space dependent absorption coefficient $k_n(r)$), the outgoing spectral directional intensity $L_n(p)$ in the line of sight t_o , characterized by the positionning parameter p , can be written as

$$L_\nu(u) = 2\, A^{1/2}(u) \int_u^R \kappa_\nu(r)\, L^\circ_\nu(r)\, ch\left(\int_u^r \frac{\kappa_\nu(r')\, r'}{(r'^2-u^2)^{1/2}}\, dr'\right) \frac{r\,dr}{(r^2-u^2)^{1/2}} \qquad (1)$$

where R is a working radius, $u= p$ (see Fig.1), $L_n{}^\circ(r)$ the Planck function and $A_n(u)$ is the transmission which is related to the absorption profile by the relationship:

$$-ln\, A(u) = 2 \int_u^R \kappa_\nu(r)\, \frac{r\,dr}{(r^2-u^2)^{1/2}} \qquad (2)$$

52)

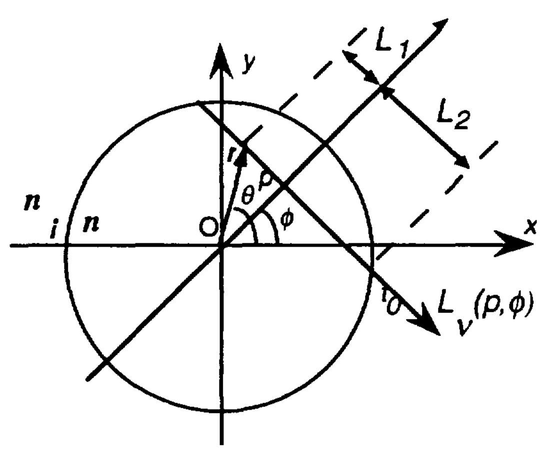

Fig.1- Geometry in a flame cross section.

Both absorption coefficient and the temperature profiles settled up in the medium may be retrieved as solutions of the coupled Volterra integral equations (1) and (2) when the projections sets $A_n(p_i)$ and $L_n(p_i)$ are known from measurements, with i= 1...20.

For the resolution of these ill-posed inverse radiative problems several methods of inversion have been used: the Abel inversion with data preconditionning, the Regularised-Adjoint-Conjugate-Gradient method, the Mollification method and the Fourier-Bessel inversion method.They were associated with special filtering and symmetrization techniques.

As a result in the lower part of the flame the absorption profiles of propane and CO2 have been reconstructed at 2980 cm^{-1} and 2280 cm^{-1}, respectively, in a satisfactionning way and the CO2 profile may be recovered at the top of the flame. Similarily, the temperature profiles have been retrieved and the results tested with thermo-couple measurements.

APPLICATION OF PHYSICAL AND OPTICAL METHODS FOR SOOT EVALUATION IN A FULL-SCALE POWER PLANT

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ABSTRACT. Over the last few years, increasing attention has been paid to the problem of reducing pollutant emissions from the combustion processes of fossil fuels. To meet the requirements concerning NOx emissions, techniques based on a fuel/air staging were utilized. It is not difficult to imagine that the effectiveness of these techniques is very dependent on boiler configuration (boiler type, excess oxygen level, burner zone heat release rate, rate of fuel air mixing, atomization quality and others) and, at the same time, these new combustion configurations can have an impact on the thermal performance of the boiler itself.
Strong efforts have been dedicated to improve the knowledge on the methods for clean combustion, but many topics in the description of the physical behaviour of a full-scale plant have not yet had a satisfactory solution. The present paper deals with one of the most important problems encountered in evaluating the performance of advanced low-pollutant combustion systems: the measurement of the concentration of combustion products that exist in form of solid particles (soot) in the combustion chamber. Experimental tests were conducted on an oil-fired 150 MWe power station (Livorno unit#1). The basic idea of the study was to develop and verify the compatibility of different techniques for measuring the extinction coefficient and volume fraction of soot in furnace. The main conclusion is that a rough theoretical analysis of the data collected by two optical methods and the information given by the application of a Lidar apparatus provide almost similar values. More detailed information available from chemical analysis, which is not yet completed, could prove to be crucial to corroborate or disprove this statement.

Tube Leakage Effect on Radiation Heat Flux in Boiler

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A common failure in the boiler furnace is tube rupture. It may cause large financial losses. An early diagnostics of tube leakage would help in preventing the failure by planning maintenance. For this reason it is of the importance to have the detection system which will give an early warning for the eventual development of the tube rupture. The detection system should be based on the reading of the selected variables which are dependent on the water leakage mass content in the flue gases. In the vicinity of the tube leakage the concentration of water vapor is increased and heat flux density distribution on the furnace wall changed. The degree of change is measure of the incident.

The aim of this paper is to investigate the sensitivity of the radiation heat flux changes due to the water leakage into the furnace. The zone method based mathematical model was developed in order to enable that analyses. The three-dimensional mathematical model describes steady-state behavior of the steam generator furnace using PISO numerical algorithm for solving conservation equations. Nine conservation equations for each control volume, including continuity, momentum, enthalpy and mass transport of fuel, oxygen, carbon dioxide and water vapor are used for determination of the temperature, velocity and concentration distributions. The combustion model is described by overall reaction rate. Solution of each conservation equation is obtained as a quasi-linear system with the additive correction multigrid technique. The Monte Carlo method is used to calculate radiation heat transfer between elementary gas and surface zones. Radiation properties are obtained by three grey gases model. The flue gas mixture radiation properties are primarily influenced by water vapor and carbon dioxide content. Boiler furnace behavior simulation results of the tube leakage conditions are represented graphically and compared with the normal operating conditions. It was shown that the radiation heat flux is sufficiently sensitive to detect the water leakage into the furnace.

SESSION 12

INVERSE RADIATION PROBLEMS III

CHAIRMAN: Y. Yener
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TR9700126

INFRARED THERMOGRAPHY FOR MEASURING THE SURFACE TEMPERATURE OF AN OXIDIC MELT

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ABSTRACT. The French Atomic Energy Commission (CEA) is conducting the VULCANO program to analyze the behavior of the melted core of a Pressurized Water Reactor in the unlikely event of a severe accident. The melted core and the melted reactor vessel structure form a mixture, named *corium*, of uranium dioxide, zirconia, zirconium and steel which can reach temperatures as high as 3000°C. We heat a corium-representative mixture above its melting point and study it while it cools down. In order to measure the surface temperature, a system combining a bichromatic pyrometer and a short-wavelength infrared thermography system is used. Since the camera is designed to measure blackbody surface temperature below 1360°C we use window glass as a filter and recalibrate the table of correspondences between the system isothermal units and temperatures. High temperature experiments have been conducted to demonstrate the feasibility of this technique. Firstly, the use of window glass as a filter is established with measurements of high temperature zirconia. Then the technique to crosscalibrate a posteriori the thermography camera images, using data from a bichromatic pyrometer measuring the gray body temperature of a small area of the melt, is described. A practical procedure is finally proposed to measure surface temperatures in the 2000-3000°C range.

A BRIGHTNESS PYROMETER TECHNIQUE FOR TEMPERATURE MEASUREMENTS IN THE FLAMES OF HYDROCARBON FUELS

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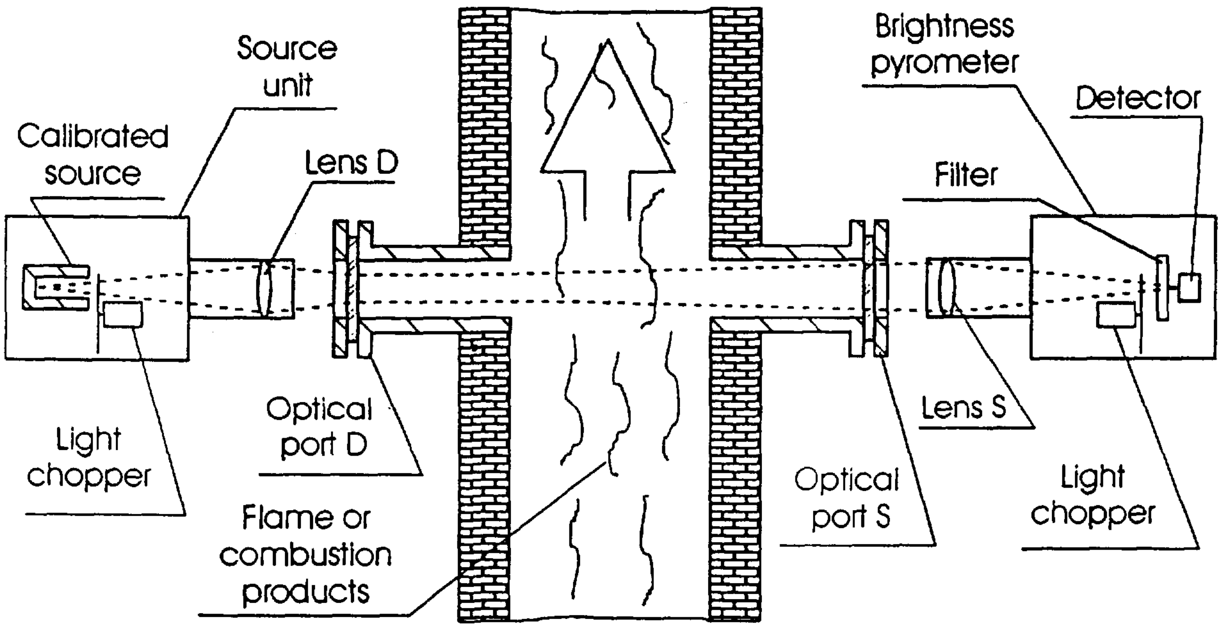
TR9700127

ABSTRACT

Optical methods has been for a long time used for a hot gas and flame temperature measurement in bench scale experiments. However, in contrast to solid - body pyrometry, they have not found yet industrial application. The subject of the present work is development of gas -pyrometer technique, that can be used to measure temperature in industrial burners with "hot" (e.g. refractory lined) walls and in other types of high temperature facilities, where the temperature is more or less uniform across the flame. The layout of the instrument is shown in the Figure. The radiant flux emitted by the hot gas (flame) F_f takes a focus by the lens S on the entrance aperture of the brightness pyrometer detector.



The radiant flux of a calibrated light source F_D takes a focus on the same aperture stop by the lenses D and S while the diameters of the optical ports of the nozzle are sufficiently large not to restrict the measured optical fluxes. To determine the flame temperature, F_f, F_D, and "source plus flame" flux F_{fD} are measured. Two groups of methods to determine a hot gas temperature T_f based on the three above signals are available - the modified line-reversal technique and the brightness pyrometer technique[1]. In the first method we obtain:

$$T_f = \left\{\frac{\lambda}{c_2}\ln\left[\frac{F_f + F_D - F_{fD}}{F_f}\left(e^{\frac{c_2}{\lambda T_D}} - 1\right) + 1\right]\right\}^{-1} \quad (1)$$

where λ is the wavelength, C_2 =.1.4388 10^{-2} m K, T_D is the brightness temperature of the calibrated source. If the brightness pyrometer is preliminary calibrated T_f can be determined by the method of brightness pyrometer from the equation:

$$T_f = \left\{\frac{\lambda}{c_2}\ln\left[\bar{\varepsilon}(e^{\frac{c_2}{\lambda T_L}} - 1) + 1\right]\right\}^{-1} \quad (2)$$

where T_L is a brightness temperature of the gas, $\bar{\varepsilon}$ is the effective emissivity of the gas defined in terms of the measured fluxes as

$$\bar{\varepsilon} = \frac{F_f + F_D - F_{fD}}{F_D} \quad (3)$$

The main sources of inaccuracy encountered in both methods include the error of the pyrometer calibration in eq.(2) and that of the source in eq. (1), error of determination of effective wavelength λ, which is identical in both methods, error of the measurement of the ratio $(F_f + F_D - F_{fD})/F_f$ appearing in eq. (1) and error of $\bar{\varepsilon}$ in eq. (2). The above suggests that the methods are equivalent from the point of view of accuracy of the measurements. Note, however, that the use of the brightness pyrometer requires no adjustment of the geometrical factors to fulfil the condition $G_S = G_D$, because the calibrated source in this case is used only for "independent" determination of the emissivity $\bar{\varepsilon}$. This may substantially simplify the requirement imposed on optical arrangement design and the alignment procedure in the field conditions. On the other hand, at $T_f \approx T_D$, i.e. close in line reversal conditions, eq. (1) reduces to

$$T_f = T_D\left[1 - \frac{\lambda}{c_2}T_D(1 - e^{\frac{c_2}{\lambda T_D}})\frac{F_D - F_{fD}}{F_f}\right] \quad (4)$$

In this case the accuracy may increase owing to the fact that the properties appear only in the small correction term. The instrument developed in this work comprises both the calibrated reference source and the calibrated brightness pyrometer and can realise both methods. If Tf is close to the steady-state brightness temperature of the source, the former can be estimated from eq.(4). If this condition does not hold T_f is calculated from eq. (2) with simultaneous indication of both the brightness temperature and $\bar{\varepsilon}$ of the gas. For measurements in the nozzle of the combustion chamber, the instrument can be mounted in situ as shown in the figure. The reference source is the model of absolute black body . The image of the source is formed in the plane of the window D, with a magnification by factor of 5. The optical ports have been specially designed to keep the windows clean. The dimensions of the optical arrangement have been selected according to ref.[2]. The measurements were made in the near infrared spectrum of combustion products in the vicinity of λ = 2.80 μm. The signals generated by the detector have been processed using the digital controller in accordance with the algorithm outlined above. The instrument has been tested both on the propane-fired burner and in the industrial high temperature blast furnace stove.

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TR9700128

SPECTRORADIOMETRIC STUDY OF THE SURFACE POLLUTION INFLUENCE ON THE RADIATIVE PROPERTIES OF ROLLING STEEL SHEETS. APPLICATION TO CONTINUOUS ANNEALING FURNACES

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ABSTRACT :

The complexity of the manufacture process, the quality and the nature of the steel industry products, require an accurate thermal treatment which are controlled through non-contact optical measurements. The radiative properties of metal sheet are important physical parameters. In fact, the emissivity governs the heating of the product. Therefore it is very important to know with precision the radiative parameters when conducting temperature measurements using optical pyrometers or for the thermal treatment optimisation.

This study therefore concerns two processes of the steel sheets elaboration : the rolling and the continuous annealing. The first process defined the dimensional characteristics of the product (thickness). Whereas the second restores its mechanical characteristics to the steel . The rolling process generate a roughness and a surface pollution constituted of oils and thin particles of iron. The radiative properties of the iron sheet can be modified by this residual film.

The purpose of this research is to study the influence of the surface pollution on the radiative properties and on the heating kinetics during the thermal treatment within the

continuous annealing furnace. For completeness, both theoretical and experimental studies were carried out.

The surface pollution film resulting from rolling operations is similar to a semitransparent medium. We built a model to calculate the radiative transfers in an isothermal semitransparent medium, for an unidimensional geometry. In the case of non-scattering semitransparent medium with a specular reflection at the interface, there is an analytical solution to the radiative transfer equations. This model uses the discrete ordinates method which offers the advantage to take into account the high anisotropies of the radiative properties at the interface.

We developed an experimental set-up to measure the directional spectral emissivity of the sheets under industrial thermal treatment conditions. This device is composed of a spectroradiometer and an annealing process simulator. It allows to heat the samples up to a temperature of one thousand Celsius degrees and to determine the spectral radiative properties within the range 2 - 14 micrometers.

We experimentally determined the principal thermophysical properties of the bare steel sheet and of the residual film (semitransparent medium). We also studied the influence of the surface morphology of the sheet on its radiative properties and we determined its optical index. The absorption coefficient of the semitransparent medium was obtained by transmittivity measurements. We compared the measured emissivity with the calculated one for different samples.

The results permit us to better understand the physical phenomena due to the surface pollution on the sheet metal. The polluted sheet emissivity strongly increases compared to that of clean sheet, even for thin films. The modification of these radiative properties causes an important over-heating of the strips within the annealing furnace.

In fact, the optimization of the industrial thermal treatment requires a on-line control of the radiative properties of the product (for exemple the reflectivity). To be efficient, this control must be done before the thermal treatment at the entry to the annealing furnace. It could be used, in a feelback loop, to react in real time the annealing furnace heating power.

Key words : emissivity, radiative properties, steel sheet, rolling oil, semitransparent medium, spectroradiometry, thermal treatment, continuous annealing.

SESSION 13

MODELING OF COMREHENSIVE SYSTEMS I

CHAIRMAN: T.-H. Song
Korea Advanced Institute for Science and Technology
Taejon, Korea

TR9700129

ABOUT THE IMPORTANCE OF RADIATIVE COOLING IN ELECTRONIC PACKAGING

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ABSTRACT. Convective cooling has received, so far, more attention than any other cooling mechanism that could be associated with the problem of electronic packaging. This is particularly interesting since the few publications where radiation has been considered show, consistently, that radiative cooling could account for 30-50 % of the total heat transfer.

In the present paper, the Discrete Ordinates method is combined with a control volume approach to simulate the thermal performance of several arrays of electronic components in situations selected to emphasize the importance of the radiation effect. The simulations include radiation combined with pure natural and pure forced convection, as well as radiation combined with mixed convection. In particular, it is demonstrated that in some applications radiation cooling can be orders of magnitude higher than convection cooling. Simultaneously, it is demonstrated that the maximum temperature of electronic components can not be correctly estimated if radiation effects are not accounted for.

TR9700130

THE RADIATIVE-CONVECTIVE INTERACTION IN LARGE-SCALE OXYGEN-HYDROGEN FIRE BALLS

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The problem of the dynamics and radiation of high temperature fire balls in free atmosphere is discussed in terms of environmental, fire and explosion safety issues, analysis of the possible consequences of nuclear and major industrial explosions[1], as well as explosions of launch vehicles at the active part of the flight[2,3].

Numerous experimental and theoretical research established that hot gas clouds rise in free atmosphere in accordance with laws that in many aspects are similar, irrespective of the causes that generated the clouds[1].

Throughout the rising process the heated gas emits heat unto the environment which results in the thermic cooling down. The main heat exchange mechanisms are convection and heat conductivity (for large-scale fire balls - effective turbulent heat conductivity). At the initial process stage the important factors are radiant losses from the heated area.

In spite of the fact that the initial stage is relatively short in terms of time, there are two reasons due to which radiation is of major practical interest. practical interest. First of all, the development of the hot cloud rise is determined to a great extent by the cloud cooling rate, which is, in its turn, depends to a great extent on voluminous radiant losses. Secondly, the data given in work[1] confirms the fact that heat radiation from fire balls generated by chemical explosions caused death to hundreds of people. Fire ball heat radiation is one of the most important hazard factors. Typical spatial and time scales corresponding to major chemical explosions were established by analysis of major accidents: fire ball radii reached hundreds of metres, while the fire balls lived dozens of seconds.

The two-dimensional numerical model has been formulated for problems involving gas dynamics and radiative heat exchange of large-scaling high temperature hydrogen-oxygen fire balls. The mathematical model is based on the system of Navier-Stokes equations, together with equations for energy conservation, selective heat radiative transfer and for continuity of water vapour and environmental air. When this model is implemented in practice at a computer, it turns out to be convenient to present the computational process in the form of three consecutive stages: gas dynamics, energy and radiation stage, that is, to implement a scheme of splitting into physical processes. With reasonable combination of global iterative solution of the whole system of equations with local iterations (for instance, between energy and radiation stages), the efficiency of computations proves to be quite high.

To solve the system of gas dynamics stage equations the method of unsteady dynamically variables[4] is applied. P1-approximation of Spherical Harmonics method is used for solution of the radiation part of the problem. The real optical and thermodynamical properties of the gases are taken into account[5,6]. The dynamics of large-scale thermics is determined by effective (turbulent) transfer coefficients[7] which allow to describe such an important element of the process as turbulent mixing of the environment.

The calculation results for large-scaling hydrogen-oxygen fire balls dynamics are presented. The following scheme was used for calculations based on the model:
- calculations in volumetric luminescence approximation,
- calculations with regard to radiant heat exchange,
- calculations not taking radiation processes into account.

In the last case neither volumetric luminescence, nor transfer of radiant energy in the fire ball were taken into account.

The numerical investigation have indicated that taking radiant heat exchange into account in the case under consideration leads to very significant changes in the results.

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Detailed Spectral Radiation Calculations for Nonhomogeneous Soot/Gas Mixtures Based on a Simulated Ethylene Jet Diffusion Flame

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Abstract

The purpose of this paper is to study the effects of the radiative properties of soot particles and CO_2 and H_2O gases on detailed radiative heat transfer calculations using a simulated ethylene jet diffusion flame. The YIX method is applied to calculate the radiative transfer quantities over the spectral range of 1-20 μm in a finite cylindrical enclosure with distributions for flame temperature, soot volume fraction, and gas concentrations precalculated from a modeling analysis. Scattering from soot particles is neglected. Soot only, gases only, and the combined cases are examined. The Rayleigh solution is used to calculate the absorption coefficient spectra for soot aggregates. Soot complex refractive index spectra are generated from the Drude-Lorentz dispersion model based on three frequently cited dispersion parameter sets. Results from these three dispersion parameter sets show that the difference in maximum flux divergence is 45% and that the difference in maximum radial flux is 62%. Thus current uncertainties about soot spectral refractive indices are the main limitation on accurate estimates of the radiation heat transfer from sooting combustion systems. The exponential-wide-band model is used to calculate gas absorption coefficient spectra. Generally, radiation from soot is two to three times of that from gases. Therefore both soot and gas contributions are significant, and accurate models for gas absorption coefficient spectra are crucial. More than 95% of the total gas radiation comes from the 2.73 and 4.3 μm bands of CO_2 and from the 2.67 μm bands of H_2O. The 6.3 μm H_2O band can be added to essentially account for all gas radiation, and other gas absorption bands make very little contribution. Practically, for the type of flames considered here, it is concluded that spectral contributions from beyond the 5 μm range can be neglected with less than 5% loss of accuracy in calculating the total radiative flux and its divergence.

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TR9700132

A Finite Element Simulation of Non Gray Participating Media Radiation for General Engineering Problems

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ABSTRACT

A numerical technique for the simulation of the effects of nongray media radiation is presented in which the wave length dependency is approximated by a number of bands. Each band is assumed to have a gray absorbing-emitting, scattering media radiation and the P-1 method is utilized to calculate the radiation flux. Inclusion of multi-layered materials as well as transparent windows and transparent bands - which allow the walls to exchange radiation energy in those bands alone - are discussed.

In this approach, the Navier-Stokes equations are solved along with the energy equation and the *n* transport equations resulting from the *n* bands of radiation, to predict the flow and temperature of radiating fluids. The coupling between the radiation equations and the energy equation is through the gradient of the irradiance flux which enters the energy equation as a source term. However, this particular formulation allows a separation of terms which leads to a redistribution of certain terms to the left hand side of the system of equations. This adds greatly to the stability of the nonlinear iterative procedure used to solve the discrete equations. These equations are implemented in FIDAP, a general purpose program for the analysis of viscous fluids.

Several examples are presented to validate the technique and also its application to 2-D, 2-D axisymmetic and 3-D problems.

The first two examples presented are comparisons with published results for a gray medium. Unfortunately, no suitable benchmark problem has been found to validate the banded-gray approach. The third example shows that the banded-gray formulation will reduce to gray provided that the spectrum under consideration is wide enough. Finally, the last two problems solved include a variety of realistic physical phenomena that are present in crystal growth and solidification problems. Both linear and quadratic quadrilateral finite elements have been employed in the simulations. The walls are assumed black unless stated otherwise.

SESSION 14

MODELING OF COMPREHENSIVE SYSTEMS II

CHAIRMAN: S. Surzhikov
Academy of Sciences
Moscow, Russia

TR9700133

COMBINED HEAT TRANSFER OF HIGH TEMPERATURE MULTI-PHASE FLOW IN THE CHANNEL WITH DEPOSITION FILM ON THE WALL AND HOMOGENEOUS VAPOUR CONDENSATION

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It's examined a problem of turbulent flow and heat- and mass transfer of high temperature gas, containing micron size polydispersed particles (droplets) and vapour of condensing media (which models the products of coal dust combustion at temperatures over 2500 K). The conditions are considered when due to radiative-convective cooling along the channel at some distance from its entrance a homogeneous condensation and appearance of sub micron droplets in the flow take place.

The existence of slag film on the wall due to droplets deposition from the flow and heterogeneous vapour condensation on the film surface is taken into account. The wall of the plane channel is considered to be metal and water cooled, which leads to formation of frozen slag layer and slowly moving liquid slag film on it.

The solution is obtained by means of splitting of the whole problem as follows: at first we predict the mean flow parameters, Stanton number and friction in the channel with chosen wall temperature; then the characteristics of homogeneous condensation are predicted and then we employ the obtained data for prediction of the deposition film thickness and radiative-convective heat transfer in it.

The first problem of radiative-convective heat transfer of multi-phase flow was solved as two-dimensional in the narrow channel approach. The turbulence characteristics of the flow were predicted by means of semi-empirical dependence. The characteristics of homogeneous condensation were predicted on the basis of kinetics equation solution with known flow velocity and bulk temperature variation along the channel. Then the first problem could be resolved with known sub micron droplets concentration and size distribution, and the following influence of flow parameters on droplets characteristics is small due to the predicted fact, that distribution function rapidly establishes after abrupt homogeneous condensation process and slowly changes along the channel (without taking the coagulation process into consideration).

In radiative fluxes predictions the particles optical properties were defined by means of Mie theory for spectral complex refraction indexes (for large droplets - on the basis of data for slag, for small droplets - on the basis of data for optical silicon glass). In view of the predicted factor of primary influence of large droplets deposition on film formation its absorption coefficient was defined on the basis of data for slag. The input of both droplets fractions was taken into account.

Mass transfer rate of the flow with film surface was predicted on the basis of semi-empirical approach. The main mechanism of large droplets deposition was considered to be the turbulent migration, of small droplets - the thermophoresis.

The problem of combined heat transfer in two-layers liquid/frozen film was solved by means of iterative algorithm for definition of film thickness, corresponding to heat- and mass transfer rates in the channel. The discrete form of energy equation and system of two-point algebraic equations for one-side radiative fluxes were solved with the aid of vector sweep method.

The results of predictions of heat transfer and film characteristics are presented for the case when radiative heat transfer rate is substantially higher, then the convective one. In the considered case of low inlet vapour and slag droplets mass concentrations (c_{v0}=0.01, c_{d0}=0.02) the contribution of small silicon condensed droplets in heat- and mass transfer is small, but micron size slag droplets make a substantial input in radiative fluxes, as well as in mass transfer rate of the flow, and hence strongly influence the film characteristics and heat transfer in the channel.

The legitimacy of the problem solution splitting method is discussed.

Modeling of a Spray Combustion with Nongray Radiation

by

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Abstract

The vaporization and combustion of liquid spray in a cylindrical combustor was numerically studied. Mixture of liquid droplets and air was assumed to be ejected from the center-hole and assisting air from the concentric annulus with swirling. Eulerian-Lagrangian scheme was adopted for the two phase calculation. The interactions between two phases were considered with the PSIC model. The effect of radiation has been evaluated by adopting the discrete ordinates method (DOM) to solve the radiative transfer equation (RTE). The weighted sum of gray gas model (WSGGM) was applied to estimate the nongray radiation by CO_2 and H_2O gases. Absorption coefficients obtained from WSGGM is used with DOM by summing solution of the RTE for each gray gas. Gas flow patterns, droplet trajectories and contours of temperature and mass fraction of the gas species were predicted with swirl number, droplet diameter, and equivalence ratio taken as parameters. Calculations showed that the vaporization and the consequent combustion efficiency were enhanced with the increase of the swirl number and with the decrease of the droplet size. Due to the effect of radiation, the gasification of the droplets occurred faster at far upstream position in the chamber, which caused a thicker flame. The exhaust gas temperature was also found to decrease.

UNSTEADY COMBUSTION OF DUST/AIR MIXTURES IN AN ENCLOSED VOLUME.

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Combustion of dust/air mixture is studied which account of convective, radiative and conductive heat transfer. A two-temperature, one-velocity mathematical model is proposed for the analysis of the unsteady processes of the combustion of the dust/air mixture in an enclosed volume. Temperatures of the particles and gas are assumed to be different. The radiative heat transfer is described by the diffusion approximation. The number of Mach is taken to be $M \ll 1$. The pressure of gas was uniform on space (homobaric flow) and only depended on time. We follow this since the high-frequency perturbations are absent and the velocity of gas small compared to the velocity of sound.
In addition, it was assumed that the forces of friction between the gas and the particles are great. Only in this case, the velocity of the gas is equal to the velocity of particles. The system of differential equations was derived in Lagrangian form. The solutions of differential equations are characterized by two different characteristic time and spatial dimensions. This results in the formation of the time and spatial boundary layers of a complicated structure that changes with variation parameters. Numerical solution involved an adaptive implicit, finite difference scheme.
Depending on the characteristics of the condensed matter (sizes and ignition temperature of the particles, a kinetic law of heterogeneous reaction), dynamic regimes of unsteady process of combustion for the suspension were investigated. Our theoretical studies are focused on the dynamic regime of combustion. The unsteady combustion regime is determined by combination of the following factors: radiative, convective and conductive heat transfer. If the chemical reaction is accompanied by the gasification of condensed phase and the radius of particles exceed the critical value , then the maximum temperature of particles, front velocity and velocity of convective flow increase. At the stage of formation of combustion processes, the convective heat transfer results in a decrease of combustion wave. Transition from slow conductive combustion to the fast radiative one has an explosive character.
If the particles absorption the gaseous oxidizer, then the rate of heterogeneous reaction, the velocity of combustion wave and maximum temperature of particles decrease. If the particle size is lower than the critical one, the convective flux leads to an increase in duration of time initiation and in limiting case this time tends to infinity.

USE OF THE 2-D COLLAPSED DIMENSION METHOD IN ABSORBING - EMITTING MEDIA WITH ISOTROPIC SCATTERING

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Thermal radiation is very important aspect of industrial processes involving high temperatures. Due to three dimensional (3-D) nature of radiation, even if fluid flow and heat transfer phenomena are two dimensional, radiation has to be treated as 3-D phenomenon. Hence for conjugate convection - conduction - radiation problems, numerous computational complexities arise resulting in increased computer time and problem formulational difficulties. The available practical methods such as Monte Carlo, Zone, Discrete Ordinate, Discrete Transfer , Discrete Intensity and Heat Ray methods have limited applications for the solution of such radiative problems. Of these only Monte Carlo method has been shown to give accurate solutions below an optical thickness of 0.1. However, Monte Carlo is expensive and hard to use in full combustion simulations. For the scattering case, the use of such methods become even more restrictive. Moreever, it is important to note that in internal clean burning combustion engines the typical optical thickness one encounters are of the order of 0.1 - 0.001. Yet because of extremely high temperatures encountered, radiation transport remains very significant in such problems.

For the first time a Cartesian based method is proposed for combustion problems involving one ordinate symmetry and absorbing - emitting media with isotropic scattering. This method collapses the 3-D radiative information of the problem into its 2-D solution plane and is applicable for all ranges of optical thicknesses while maintaining almost analytic accuracy. To accomplish this task, this method makes use of effective intensity rays (EIR) each of which contains the information of a plane of real intensity rays perpendicular to the solution plane. As demonstrated in the reference A, this novel procedure thus eliminates the use of solid angles from the formulation and reduces both the complexity and computational expense involved in the solution of such problems.

Reference (A):David A. Blank,' The Cartesian Collapsed -Dimension Method for use in Numerical 2-D Radiation Calculations in Absorbing-Emitting Media', Int. J. of Numerical Methods in Engineering, Vol. 37, No. 18, pp. 3023-3036, 1994.

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POSTER SESSION 1

TR9700137

ACCURATE SEGMENTATION OF COMPLEX SATELLITE SCENES

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ABSTRACT: Accurate cloud detection in Advanced Very High Resolution Radiometer (AVHRR) data over land is a difficult task complicated by spatially and temporally varying land surface reflectances and emissivities. The AVHRR Split-and-Merge Clustering (ASMC) algorithm for cloud detection in AVHRR scenes over land provides a computationally efficient, scene specific, objective way to circumvent these difficulties. The algorithm consists of two steps: 1) a split-and-merge clustering of the input data (calibrated channel 2 reflectance, calibrated channel 4 temperature, and a channel 3 - channel 4 temperature difference) which segments the scene into its natural groupings; and 2) a cluster labeling procedure which uses scene specific joint three-dimensional adaptive thresholds (as opposed to constant static thresholds) to label the clusters as either cloud, cloud-free land, or uncertain. The uncertain class is used for those pixels whose signature is not clearly cloud-free land or clouds (e.g., pixels at cloud boundaries which often contain subpixel cloud and land information which has been averaged together by the integrating aperture function of the AVHRR instrument). Results show that the ASMC algorithm is neither regionally nor temporally specific and can be used over a large range of solar altitudes. Sensitivity of the segmentation and labeling steps to the choice of input variables also was studied. Results obtained with the ASMC algorithm also compare favorably with those obtained from a wide range of currently used algorithms to detect cloud over land in AVHRR data. Moreover, the ASMC algorithm can be adopted for use with data to be taken by the Moderate Resolution Imaging Spectrometer-Nadir (MODIS-N).

The accurate segmentation of sea ice from cloud and from cloud-free ocean in polar AVHRR imagery is important for many scientific applications (e.g., sea ice - albedo feedback mechanisms, heat exchange between ocean and atmosphere in polar regions; studies of the stability of surface water in polar regions). Unfortunately, it is a difficult task complicated by the common visible reflectance characteristics of sea ice and cloud. Moreover, AVHRR channel 3 data historically have been contaminated by highly variable sensor noise which generally has hampered their use in the classification of polar scenes. Likewise, polar scenes often contain pixels with mixed classes (e.g., sea ice and cloud). This paper uses a combination of fuzzy logic classification methods, noise reduction in AVHRR channel 3 data using Wiener filtering methods (Simpson and Yhann, 1994), and a physically motivated rule base which makes effective use of the Wiener fil- tered channel 3 data to more accurately segment polar imagery. The new method's improved classification skill compared to more traditional methods, as well as its regional independence, is demonstrated. The algorithm is computationally efficient and hence is suitable for analyzing the large volumes of polar imagery needed in many global change studies.

TR9700138

SIMULATION OF THE EXTINCTION OF A LASER BEAM USING THE MONTE CARLO METHOD

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ABSTRACT

Extinction of light in participating media has been extensively used in applications such as laser diagnostics and inverse radiation problems. The accuracy of these techniques is always judged upon the adequacy of the underlying modeling. In that sense, the rigorous modeling of the radiative phenomena is expected to improve substantially the accuracy of the applied techniques. In the present paper a direct statistical Monte Carlo method is adopted, together with detailed treatment of the radiative properties of particles calculated using the Mie theory. The method is firstly applied for the experiment of Boothroyd et al.(Boothroyd, S.A., Jones, A.R., Nicholson, K.W., and, Wood, R., Combust. Flame 69, 235-241, 1987) concerning extinction of an expanded laser beam by fine streams of fly-ash particles. This experiment is depicted in Fig. 1. For sampling of the directions followed by the bundles after a scattering event the exact, according to Mie theory, phase function is used. The effects of polarisation is not taken into account, since the laser beam is appropriately prepared to simulate unpolarised light. Comparisons are made between the measured and calculated angular distribution of the intensity and satisfactory agreement is found (Fig. 2). The value of the fly-ash refractive index is initially taken as suggested by the authors ($n+ik=1.5+i0.012$).

Due to the uncertainties concerned to the dependence of the refractive index from the chemical composition of the ash, as well as the sensitivity of Mie calculations on this index, lower values of its imaginary part are considered, as measured by Goodwin and Mitchner (Goodwin, D.G., and Mitchner, M., Int J. Heat Mass Transfer, 32, 627-638, 1989) This consideration reveals significant discrepancies of the calculated angular intensities (Fig. 3). For the specific wavelength of the He-Ne laser, a backward lobe is apparent for all the diameters of the examined psd. The most drastic change is concerned with the alteration of the scattering behavior. The calculated scattering albedo was found in the order of 0.99. Thus, ashes characterised by imaginary part of the refractive index as low as measured by Goodwin, are almost conservative scatterers.

The concentration of the ash particles in the previously examined experiment is found to be dilute enough to practically avoid multiple scatterings. In order to gain a better insight on this phenomenon, a numerical experiment is performed concerning the extinction of the same laser beam by a suspension of particles with considerably higher optical depth. At elevated concentrations, bundles undergo multiple scatterings before reaching the photomultiplier. This procedure is quantified by calculating the ratio of the bundles reaching the photomultiplier after multiple scattering over the total number of the received bundles. The angular distribution of this ratio is presented in Fig. 4. From this figure it is evident that for a wide angular interval the received scattered intensity originates mostly from multiple scatterings. From the same figure, angular positions where this ratio

is minimised are easily identifiable. Furthermore, the comparison between the angular distributions of the singly scattered bundles and totally received ones imply that a medium tends to be sensed as an increasingly isotropic scatterer as the proportion of the multiple scatterings also increases.

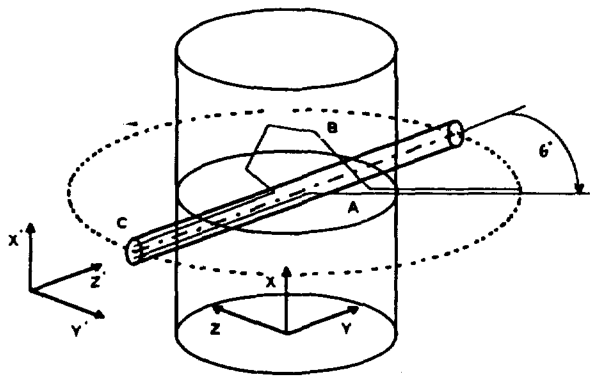

Figure 1. The simulated experiment
A: Single scattering
B: Multiple sscattering
C: Laser beam

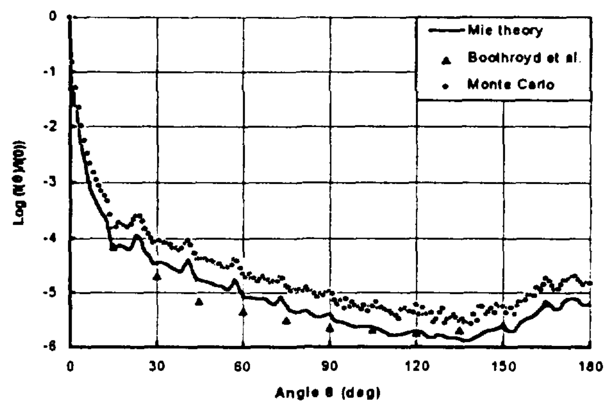

Figure 2. Angular distribution of the normalised scattered intensity

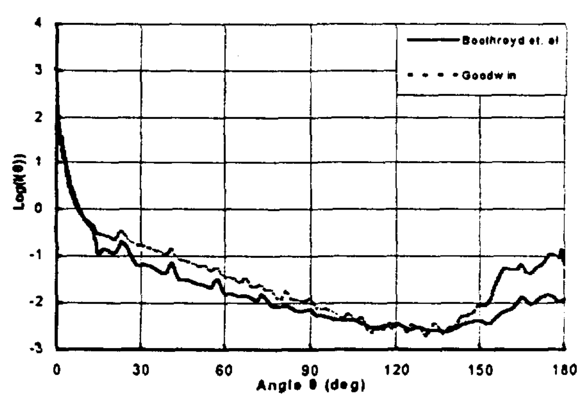

Figure 3. Comparison of the angular distribution of the scattered intensities using different complex refractive indices

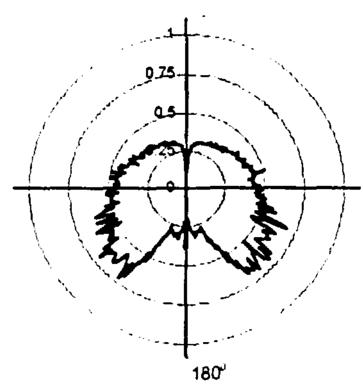

Figure 4. Ratio of the multiply scattered to the totally received intensities

DEPENDENCE OF RADIATIVE TRANSFER CHARACTERISTICS FROM GEOMETRY OF AN ABSORBING, EMITTING AND SCATTERING MEDIUM

TR9700139

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For power production systems, it is necessary to know the values of the incident and net radiant fluxes and their distributions along the boundary surfaces. However,the analysis of literature shows that these problems are not enough investigated yet. In present work the theoretical investigation of the influence of geometric form of an absorbing,emitting and scattering medium on the incident radiant flux and its distribution along the boundary surface is proposed. The problem is solved for a closed two-dimensional domain.

The presented investigation is based on the numerical solution of the well-known integro-differential equation of radiative transfer with the boundary conditions which are including the radiation and reflection processes on the heat-absorbing surfaces. Resolution algorithm of the mentioned above equation is a combination of the finite element method , discrete-ordinate method and method of iterations. The idea of this method is following: a) according to the discrete ordinate method, few directions for calculation are selected and the mentioned above equation is written for every selected direction; b) obtained equations are solved by well-known method of finite elements; c) so as the radiative transfer equation is non-linear an iteration process is organized for calculation the values of the radiation intensity at the nodes of the considering domain.

On the base of proposed method the dependence of radiative characteristics (density of incident and net radiative fluxes , structure of radiation field, e.t.c.) from geometrical form of an absorbing, emitting and scattering medium is researched for domains with various geometry. The results of investigations show possibility of discontinue the radiant flux density at the corner point of domain. It is shown that the discontinue take place on the condition when the bisector of corresponding corner is not the symmetry axis of the domain or the optical properties of medium. The influence of the optical and geometrical properties of medium on the values of discontinue is considered. The behavior of falling radiant flux distribution along the boundary for various optical, heat-physical and geometrical characteristics of medium is investigated. It is shown that inhomogeneity of this distribution is increased with the increasing relative difference between the boundary radiation and the own medium radiation. The carried out investigation shows that the form of domain filled with an absorbing, emitting and scattering medium essentially effects the radiant flux distribution along its boundary surfaces.

Authors are thankful to the Belarus Foundation of Fundamental Investigations for the financial support of this work.

DEPENDENCE OF RADIATIVE TRANSFER CHARACTERISTICS FROM OPTICAL PROPERTIES OF AN ABSORBING, EMITTING AND SCATTERING MEDIUM

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TR9700140

Study of the mechanism of radiation propagation in two-phase media (gas and solid particles) has a significant number of applications in applied physics and engineering. These include radiative and combined heat transfer, direct and inverse problems in spectroscopy of scattering medium, heat transfer enhancement in thermal and nuclear engineering and metallurgy and so on.The development of modern technology and enhancement due to the increasing capacity of heat power plants have influenced a growing interest in radiative heat transfer in new types of equipment.As a result, new, more stringent requirements for analysis of radiative transfer and correct and timely solutions of problems in this field are needed. At present time many methods for resolution of transport equation are known. But these methods do not estimate complex geometrical form of real objects.That is why the authors propose a resolution method for the integro-differential equation of radiative transfer, which is free from mentioned above demerit at least.

Numerical solution of the well-known integro-differential equation of radiative transfer with the boundary conditions which are including the radiation and reflection processes on the heat-absorbing surfaces.Algorithm of resolution of the mentioned above equation is a combination of the finite element method,discrete-ordinate method and method of iterations. The idea of this method is following: a) according to the discrete ordinate method,few directions for calculation are selected and the mentioned above equation is written for every selected direction; b) obtained equations are solved by well-known method of finite elements; c) so as the radiative transfer equation is non-linear an iteration process is organized for calculation the values of the radiation intensity at the nodes of the considering domain. In the report this method is described in full details.

On the basis of proposed method the dependence of radiative characteristics (density of incident and net radiative fluxes, structure of radiation field, e.t.c.) from optical properties (optical density of medium, Shuster's number, emissivity of boundary and so on) of an absorbing, emitting and scattering medium is researched. In particularly the results of investigation show that scattering processes may increase or decrease the value of leaving radiant intensity in dependence on the optical thickness of medium along the direction of propagation. This result is important for the definition of absorbing index of selective, absorbing, emitting and scattering medium in the finite spectral range and for diagnosing of such media.

Authors are thankful to the Belarus Foundation of Fundamental Investigations for the financial support of this work.

TR9700141

COMPARISON OF NUMERICAL QUADRATURE SCHEMES APPLIED IN THE METHOD OF DISCRETE TRANSFER

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Keywords: Thermal Radiation, Discrete Transfer, Integration.

ABSTRACT

The quadrature scheme in the method of discrete transfer is considered. Since the numerical solution of the radiation problem is very time consuming, it is of the utmost importance that the most efficient numerical quadrature schemes be applied in order to obtain a solution with a prescribed accuracy with the minimum computation costs. Little research has been performed in this area and only two schemes have been put forward by Shah (1979) and Bressloff et al. (1995). Shah (1979) suggested a scheme in which the peripherential angle (Φ) and the angle (θ) from the normal of the wall are divided into equal size angles. This type of discretisation leads to solid angles which are highly unequal and the scheme is a simple midpoint quadrature in the Φ,θ space. Bressloff et al. (1995) suggested a quasi-equal solid angle discretisation of the hemisphere and obtained a better accuracy for the same computational cost. In the present paper, the Gauss-Legendre quadrature is applied for the integral of the irradiation written in three ways: (i) as a function of Φ,θ (ii) as a function of Φ,μ ($\mu=\cos\theta$), and (iii) as a function of $\Phi,\frac{1}{2}\mu^2$. Furthermore, (iv) the quadrature scheme known from the method of discrete ordinates is applied. The quadrature schemes are compared for simple geometries with an isothermal absorbing, emitting gray gas with a prescribed constant temperature regarding the accuracy and computational costs.

TR9700142

BOUNDARY CONDITION FOR RADIATION MODELLED BY HIGH ORDER SPHERICAL HARMONICS

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Keywords: Radiation, Spherical Harmonics, Marshak Condition.

ABSTRACT

A recurrence formula is derived for coefficients in the Marshak boundary condition which is used in connection with the method of spherical harmonics when modelling radiation heat transfer in absorbing, emitting and scattering material. The case considered is a one-dimensional layer of material with azimuthally symmetry surrounded by opaque, diffusely and specularly reflecting and diffusely emitting walls. The other coefficients in the Marshak condition are related to the first mentioned coefficient by simple expressions. This new method of calculating the coefficients by recurrence is easier to apply than deriving the boundary condition by tedious manual integrations. A recurrence formula for the cumulated errors is derived and the analyses shows that acceptable low errors occur when using the appropriate type of floating point numbers in the computer program taking into account the approximation order. The coefficients found by recurrence are compared to coefficients found by numerical integration and in one case the analytical solution and the agreement is excellent. The application of the recurrence formulas is demonstrated using a computer program solving the equations of the method of the spherical harmonics for arbitrary approximation order. The intensity as function of the direction cosine at the walls is analyzed for approximation orders up to 41. High order approximations are necessary for accurate modelling of the intensity as function of the direction due to discontinuities at the walls.

RADIATION IN HYPERSONIC IONIZED TURBULENT GAS JETS

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The object of the work has been the development of a semiempiric design model for radiation-convection heat-mass exchange in reactive chemically jet flows, including a technique of radio band radiation design. The design technique for electromagnetic radiation of ionized jets based on the solution of the equation of radiation transfer in isotropic medium, taking into account electromagnetic waves radiation, refraction and absorption. According to this model a basic source of the electromagnetic radiation in the radio band is bremsstrahlung, provided for interaction of electrons and heavy neutral particles. In this case a kinetic model of plasma may be described by Boltszmann equation for electrons in which the collision integral is proportional to the frequency of electrons and neutral particles. In order to simulate the hypersonic axial-symmetric jet flow it has been proposed in this work the mathematics model based on the solution of the stationary system of the equations in partial derivatives of parabola type, including the parabolized system of Navier-Stokes equations (in projection onto transverse and longitudinal coordinate axes); the equations for kinetic energy and velocity of turbulent pulsation dissipation (the K- ε model of turbulence), the energy equation, the diffusion equation for components and mixture elements, as well the equations of chemical kinetics and the radiation transfer equation. In order to attain numeral count stability the equations of continuity with the artificial viscosity have been used in this system of equations. The equation of energy regarding to temperature has been applied, so it has been allowed to reduce an iterative process of its determination and to rise a count rate essentially. The presented technique for chemical kinetics design allows to design both non-equilibrium and equilibrium chemical processes. Newton s method has been used for the solution of the system of the non-linear algebraic equations, determining an equilibrium composition of a mixture. It is a model of low ionized plasma, that has been applied to determine a degree of jet flow ionization. According to this model the basic chemical reactions are isolated to be used for determination of a basic chemical composition, pressure, density and temperature of a mixture.

For the numeral solution of the parabolized system of the equations, cited above and offered for heat-mass transfer in reactive chemically jet flows, an algorithm has been proposed in which an implicit numeral scheme according to the "predictor-corrector" method has been used. On the basis of numeral simulation the investigation of heat-mass exchange and radio frequency radiation of a hypersonic under expanded jet, while its discharging into hypersonic air flow, has been worked out. As a result of the numeral computations been fulfilled the basic hydrodynamic and heat parameters distribution have been determined, such as: velocity, pressure, temperature, basic components concentration, including electrons concentration and spectral intensity of radio radiation.

TR9700144

RADIATIVE TRANSFER IN SEMI-TRANSPARENT MEDIUMS LIKE ISOLATING FOAM AND GLASS WOOL

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Abstract :

There are several engineering applications of simultaneous radiation and conduction in a participating medium. For exemple, in heat transfer at room temperature through porous insulating materials such as fibers and foams, thermal radiation is comparable to conduction.

In such situations a separate calculation of conductive and radiation heat fluxes without any consideration of the interaction between thermal radiation and conduction may introduce error in the heat transfer results.

For the fibrous insulants an accurate modelization allows the simulation of radiative transfer starting with the optical and morphological characteristics of the medium. The absence of simplifying hypothesis allows the study of parameters influencing the transfer.

This method is impossible for the foams because the optical and morphological characteristics are complicated or unknown.

A experimental and a phenomenological approach are necessary. Measurements of thermal conductivity, using a k meter guarded hot plates apparatus, showed that the steady state thermal conductivity depends of the specimen thickness.

We make use of this property and induce the extinction parameter for the radiation transfer. The energy equation for simultaneous conduction and radiation may be solved.

Particularly the phenomenological approach for the fibrous insulants are analysed and compared with the rigorous model showing a good agrement.

TR9700145

NON-STEADY RADIANT HEATING OF A COMPOSITE SLAB

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ABSTRACT This paper describes a method of predicting the thermal response of a two-dimensional composite slab which is subjected to non-linear thermal boundary conditions and which has temperature-dependent physical properties. One of the exposed faces of the composite slab is subjected to a time-dependent radiative flux whilst the other face is exposed to the ambient fluid and a radiation sink. Thus the boundary conditions involve both counteracting and combined radiative and natural convective heat transfer, which are both non-linear in temperature. The conduction equation itself becomes non-linear when the physical properties (such as conductivity) are temperature dependent. Additional problems arise from the presence of discontinuities in physical properties at the interfaces of the slab components. The analysis was developed in order to predict the temperature distribution in a composite plate rotating backwards and forwards in a beam of thermal radiation.

This problem poses considerable challenges for the analyst; of all the available methods of solution the heat balance integral (HBI) technique is particularly well suited. Of central importance to the accuracy of the HBI technique is the choice of approximation for the time-dependent temperature profile in a spreading thermal disturbance and the main contribution of this paper is the presentation of an integral solution to this complex transient conduction problem which uses Hermite polynomials as the approximations for the temperature profile.

ON THE HEAT TRANSFER PHENOMENON IN A BODY WITH WAVELENGTH-DEPENDENT PROPERTIES

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ABSTRACT. In this work the coupled conduction/radiation heat transfer phenomenon in an opaque convex body with radiation properties depending on the wavelength is mathematically modelled. The considered heat transfer process is described by a partial differential equation subjected to a nonlinear boundary condition which involves the Classical Planck's law. In order to provide a more adequated description, it is constructed a modified version of Planck's law. It is presented a minimum principle which is employed for proving existence and uniqueness of the solution and which provides a way for simulating the considered nonlinear energy transfer phenomenon.

POSTER SESSION 2

TR9700147

METHOD OF RADIATIVE COEFFICIENTS AND ITS APPLICATION IN THERMAL CALCULATIONS OF PRACTICAL INDUSTRIAL CASES

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Considering heat exchange equipment in general, heat transfer is usually a combined process consisting of conduction, convection and radiation. In calculation procedures there is a need to determine a certain strategy taking into consideration a prevalent component of heat transfer, the influence of other components, the degree of simplification of a mathematical model being created, available data from experiment, the ratio of operation etc.

The application of the method of radiative coefficients has proved itself to be an efficient and useful tool for the evaluation of the radiative component of combined heat transfer in various industrial cases.

The dependence between the temperature of surfaces and the heat fluxes in an enclosure with isothermal gas is defined by a set of non-linear algebraic equations. By their modification, a direct expression of the radiative heat flux at the surface has been obtained through radiative coefficients and source and sink temperatures. Radiative coefficients can be determined analytically for some fundamental systems - infinite parallel plates, part of plate and enclosing area, infinitely long cylinders and concentric spheres. These systems are represented by an enclosure consisting of two surfaces with given emissivities and temperatures filled with gas of a known constant temperature. Radiative coefficients are functions of configuration factors, emissivities of surfaces and emissivity of gas for determined mean beam length dependent on the system in question .The application of this method is very effective especially in the case of simple isothermal enclosures consisting of two surfaces with given emissivities and temperatures, filled with gas of a known temperature.

Using the method of radiative coefficients, quite new and original methods for the evaluation of the radiative component in the case of combined heat transfer have been developed. The creation of these methods was initiated by attempts to solve industrial cases.

The mathematical model for the evaluation of the radiative component in the case of bare tube banks/bundles considers individual tubes surrounded by gaseous layers. The actual surrounding volume of these layers was substituted by an equivalent cylindrical surrounding volume for the simplification of geometry to be able to apply the fundamental system with infinitely long cylinders. The main result of the calculation is the evaluation of heat flux density at the tube outer surface which is represented by the inner cylinder of the substituting system. Consequently the radiative heat transfer coefficient is evaluated.

As an application the thermal calculation of the heat exchanger primary reformer - type TANDEM can be mentioned. The radiation shares on the total heat flux with 18 to 30% dependent on the number of baffles in this special shell-and-tube heat exchanger.

The mathematical model based on the method of radiative coefficients can be incorporated into any program used to predict the thermal performance of a tubular heat exchanger and/or of a convective section with bare tubes in a furnace. A computer program based on the above method has been incorporated into HTRI software.

A method for comparatively simple calculation of combined heat transfer in the case of finned tubes (convection + radiation + conduction in fins) is compatible with the above method for calculation of heat transfer in the case of bare tubes. The application of the method of radiative coefficients is a common point of the two methods. The resulting value of heat flux density is given by the product of this value in the case of bare tubes, correction factor for fin thickness and above all the heat flux multiplicator which expresses the fins influence from the radiation point of view. This factor is given by the ratio of the radiative heat flux on the tube surface in the case with the presence of fins and that on the bare tube surface. The values of both heat fluxes can be obtained by solving equations of the heat balance for surface zones (using a simple application of the zone method) considering conduction in fins. In the case of calculating a convective section in the furnace, considering cooling the flue gas from about 400°C to 250°C the share of the radiative heat transfer is around 6%.

A model for the calculation of the radiative heat flux from a radiation chamber to the shield tubes of a furnace and the evaluation of the radiative heat transfer coefficient as a boundary condition in calculating temperature distribution using the method of finite elements can be considered as another applications of the method of radiative coefficients.

Relatively simple procedures based on this method have been developed with the purpose of being convenient for practising engineers. These procedures are based on some simplifications enabling the evaluation of the radiative component in combined heat transfer. Computer programs enable us to explore the sensitivity of selected parameters as a result of e.g. the variation in geometrical parameters and operation conditions.

METHODS FOR MODELLING PROCESS FURNACES

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Furnaces are inherent equipment in many processes in both the chemical and petrochemical industry. In a number of this processes, particularly in those for bulk chemical production, a process furnace forms the core of the chemical/petrochemical plant. It is quite usual that cost of the furnace system ranges between 10 and 30 % of the total investment and, as for the operating cost, fuel burned in the furnace can represent up to 90 % of the energy bill. It is therefore evident that furnace design methods play an important role. An experimentally verified mathematical model which enables us to simulate the behaviour of various arrangements of furnace system belongs to a list of designer's powerful tools. The application of the model in assisting effective operation is of even greater importance.

The basic requirements and aspects concerning the methods for modelling have to be specified in connection with the choice of methods (the purpose, use and the field of application of a mathematical model, the complexity of furnace geometry, the input data available for simulation, etc.). Two different approaches are presented:

(i) the first one deals with a detailed and complex mathematical model for a specific purpose;
(ii) a simple mathematical model convenient for rapid calculation of tubular fired heaters is the subject of the second one.

The mathematical model of a radiation chamber in steam reforming based on the zone method (i) is a result of long term research. It enables us to simulate thermal chemical processes both in the combustion space and inside the reaction tubes. This model was verified by measurements in a process plant.

A complete mathematical model capable of simulating the conditions in a reaction furnace is formed by connecting the combustion space model with that of reactions inside the tubes During its development the model has passed through several stages due to its continuous confrontation with the plant data and measured values obtained in the specially designed testing programme on an industrial size steam reformer furnace. The permanent comparison of calculated and measured values has made it possible to introduce a few simplifying assumptions and some improvements in the practical application of the zone method. A two dimensional section of radiation chamber cross-section can be considered for modelling. This section is limited by two tube rows which are considered as so called "specled walls". An approximative way for the fast evaluation of direct exchange areas has been developed based on analytical relations and approved comparing the resulting values with those obtained using the Gaussian method for numerical integration. The real gas (flue gas) is substituted by three gray and one diathermic component. A universal set of absorption coefficients independent on temperature and gas composition was used which is advantageous for repeated calculations (e.g. different regime of furnace operation) because direct exchange areas can be calculated only once. As the calculations in the early developmental stage of a model considering plug flow of flue gas led to an unrealistic maximum of the tube outer surface temperature (compared with the measured one) a suitable level of back mixing, based on flue gas flow visualization, has been introduced into the model.

By means of the model the influence of selected parameters on main characteristic quantities in steam reforming was investigated, a method for steam reforming design was developed (and applied in practice) and a knowledge base for fuzzy expert system was created. The widest possible application of the verified mathematical model is obviously in the sphere of furnace operation in technological processes. The model enables technologists and operators to simulate expected operation conditions.

The simple mathematical model of furnaces (ii) based on Hottel's One-Gas-Zone Method is extended a verified. The mathematical model is constructed in such a way as to enable the calculation to be applied to any tubular fired heater. This implies that the furnace with an arbitrary geometry and consisting of both radiation chamber and convective sections can be calculated. The computer program based on this model basis involves two major alternatives for calculation. The first one deals with complete calculation of process fluid heating inside tubes by considering the pressure drop. In the second one the model of heat transfer inside the tubes is replaced by given values of the heat transfer coefficient and input/output temperature of the medium.

Special attention is given to a model for the calculation of heat flux from a radiation chamber to the shield tubes. Heat flux at the shield tubes is evaluated using the application of the method of radiative coefficients for an enclosure where the analytical solution is known. Assuming the radiative heat transfer from the radiation chamber flue gas to the shield tubes is approximated by that of an equivalent gaseous volume belonging to the shield tubes and surrounded by two surfaces - the absorbing one (shield tubes transferred to the "specled wall") and the radiatively adiabatic one, substitution by a simple fundamental system is feasible and the radiative heat flux density at the tube surface can be evaluated.

The radiative component of heat transfer is also considered in the calculation of convective sections.

Compared with the model based on the zone method a simple mathematical model for relatively rapid calculations for process furnaces provides designers and operators with a useful tool in those cases where distribution of temperatures, heat fluxes and other quantities are not required. An algorithm for a furnace with arbitrary geometry consisting of radiation chamber and convective sections has been created. Special emphasis was laid on simplicity and universality.

This model proved itself to be very useful in a new method for effective furnaces integration into processes based on Pinch Technology.

TR9700149

MONITOR SYSTEM FOR RADIATION TRANSFER

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Monitor System for Radiation Transfer (MSRT)is an interactive computer system intended for creating radiative models.

The concept "radiative model" includes the following notions:
- optical model (spectral, group and total absorption and emission coefficients);
- model for radiation heat transfer.

This interactive system consists of the following three parts: Base of Models, Data Base, Software.

1. Base of Models.
This part of the MSRT consists of the program modules which are realize the mathematical models of radiative processes in gases, plasma, dispersive media:
- The calculation methods for modeling of elementary radiative processes: probabilities and cross-section at the bound-bound, bound-free and free-free transitions; oscillator strengths, Franck-Condon factors; modeling of scattering processes by theory Mie;
- The calculation methods for modeling of complex radiative processes in gases and plasma: the group and spectral models of low temperature plasma optical properties: absorption coefficients, half-spherical emission capability, Plank and Rosseland coefficients.
- The calculation methods for problem of radiative transfer in selective-emitting, selective-absorbing and selective-scattering media.

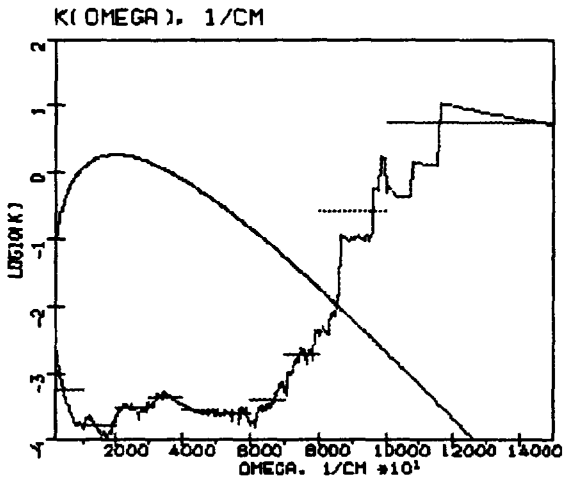
2. Data Base
This part of the MSRT contains the following data:
- probability, cross-section, rate constant;
- spectroscopic properties of the particles (atoms, molecules, ions).

3. Software
This part of the MSRT consists of computer implementation of the models, service procedures, program modules for data manipulation.

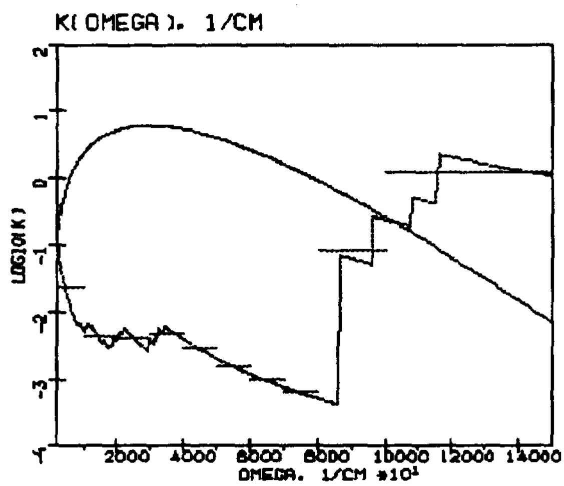
At the present time MSRT contains information about following components: H, He, C, N, O, Na, Mg, AL, Si, Ar, K, Ca, N-, O-, O2, N2, NO, C2, CO, CN, H2, C3, H2O, CO2, CO+, N2+, SiO, NO2, He(+1), He(+2), C(+1)-C(+5), N(+1)-N(+5), O(+1)-O(+5), Na(+1)-Na(+5), Mg(+1)-Mg(+5), Al(+1)-Al(+5), Si(+1)-Si(+5), Ar(+1)-Ar(+5), K(+1)-K(+5), Ca(+1)-Ca(+5). Temperature range: 1000-20000-150000 K, pressure range: 0.001-100 atm.

The different radiative models are presented: spectral absorption coefficients of low-temperature plasma with atomic lines structure, "smeared rotational line" absorption coefficients for diatomic molecules, absorption coefficients of diatomic molecules with rotational line structure.

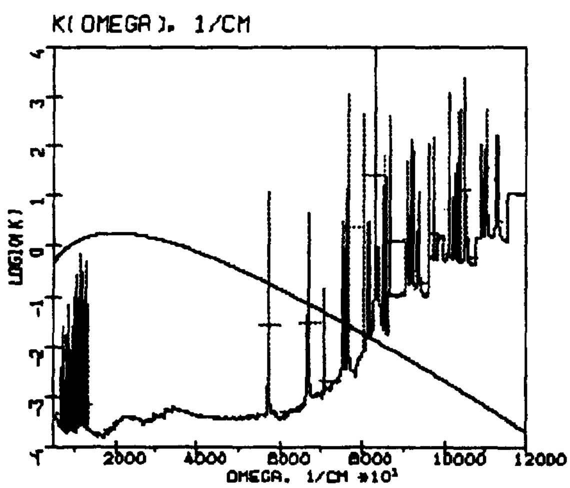
For example, the figures show spectral absorption coefficients of air plasma without and with atomic lines structure.



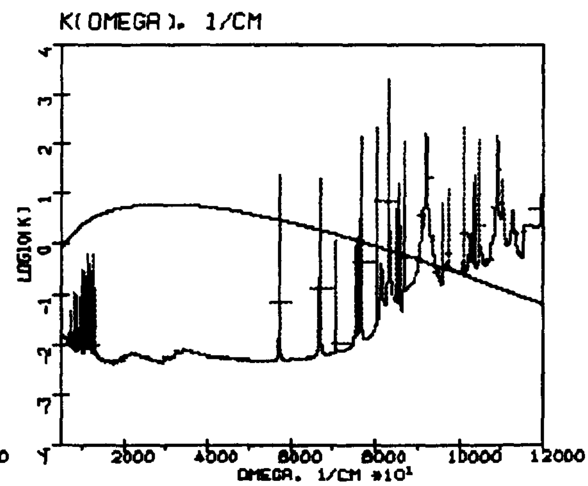
T= 10000 K. P = 1.0000 ATM
RO= 0.0173 KG/M**3



T= 15000 K. P = 1.0000 ATM
RO= 0.0079 KG/M**3



T= 10000 K. P = 1.0000 ATM
RO= 0.0173 KG/M**3



T= 15000 K. P = 1.0000 ATM
RO= 0.0079 KG/M**3

TR9700150

THE INTERACTION OF RADIATION WITH CONVECTION IN SUBSONIC LAVAL NOZZLES OF LASER'S PLASMA ACCELERATORS

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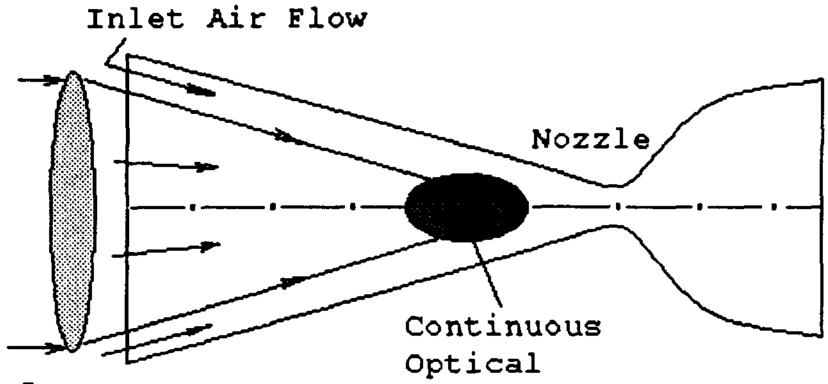
The laser-heated plasma accelerator (LHPA) operation is based on the phenomenon of stationary existence of a low-temperature plasma (continuous optical discharge, COD) in a focused laser beam (as a rule, CO_2-continuouswave laser)[1-3]. The major parameters of LHPA are[1-5]: temperature region - 300-20000 K, pressure - 1 atm, inlet velocity - 1-100 m/s, nozzle length - 20-30 cm, height of the plane Laval nozzle critical section - 1-2 cm.



The LHPA operation mode is determined by the following set of parameters[4,5]:
- the laser radiation power, the laser radiation wave number, the quality and geometry o the beam, and time characteristics of laser radiation;
- type o gas and working pressure;
- the velocity and the spatial distribution of gas flow in the vicinity of COD;
- the structural peculiarities of the gas dynamic flow, first of all, the channel shape and the manner of gas flow supply and heating.

Physical and mathematical models of radiative-gas dynamic process in an subsonic Laval nozzle of laser-heated plasma accelerator operating in the mode of radiative combustion of a continuous optical discharge are described.

The evolution of temperature and gas dynamical haracteristics distributions in the laser radiation field in a Laval nozzle is described by a system that comprises the two-dimensional equations of conservation of energy, the continuity and Navier-Stokes equations, the equations of selective thermal radiation transfer (in the form of a multigroup P1-approximation of the spherical harmonics method), and laser radiation transfer (in the geometrical optics approximation)[5].

The implicit-explicit numerical method is developed for solving the self-consistent equations system in a curvilinear calculated grid. Because the pressure variation was small, only the temperature dependence of the thermodynamic, optical, and transport properties of the gas was taken into account. The main iteration process was organized using the equations of conservation of energy and the equations of transfer of selective thermal and laser radiations. At this stage, we were in fact solving the truly nonstationary problem of radiative-conductive heat exchange. On reaching the convergence of the iteration process at each time step, the iteration solution of the system of gasdynamical equations was started, after which all of the indicated iteration processes were repeated untill a full convergence of the unknown functions at a time step was reached.

The results of numerical modelling of subsonic air flow in various Laval nozzles are discussed. The parameters of LHPA operating under conditions of radiative combustion of COD are found by calculations, and conditions are established under which stationary eddy flow structures may be expected to occur because of a large gas mass flowing around the COD combustion region. The calculation results make it possible to point out one of the probable mechanisms of COD stability loss in a gas flow, namely, the mechanism associated with the occurrence of intense vortex motion behind a discharge. This suggests sum means of improving the efficiency of operation of power devices of the indicated class.

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THE EFFECT OF ASH PARTICLES' COMPLEX REFRACTIVE INDEX ON RADIATIVE HEAT TRANSFER WITHIN A BOILER FURNACE

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A three-dimensional mathematical model for predicting turbulent flow with combustion and radiative heat transfer within a furnace was developed. The model consists of two linked sections: (1) the transport equations which are nonlinear partial differential equations solved by a finite difference scheme, and (2) the radiative heat transfer which was analyzed by the zone method. The Monte Carlo method was used to evaluate total radiative interchange in the system between the zones. An existing rigorous theory of interaction between infrared waves and solid particles developed for several simple particle geometries was used. The resulting set of equations, called the Mie equations, enable the calculation of absorption and scattering coefficients, for given particle shape, particle size, complex refractive index, mass concentration, density of particle materials, and wavelength of the incident radiation. With this model the series of calculations with varying gas radiative properties models, loads, types of fuel, excess air, burner tilt angles, and several particle parameters can be performed. The effects of these variables on the gas temperature and heat flux distribution within the furnace can be studied.

The mathematical model was previously validated against experimental data collected on two large furnaces by comparison of the measured and predicted gas temperature and heat flux distribution. The purpose of this paper is to study only the influence of the ash particles' complex refractive index on the radiative heat transfer within the furnace of a pulverized-coal-fired boiler. The method of approach is mathematical modelling and simulation. Three various complex refractive indices (for three particle materials: soot, alumina and simulated ash) were considered. The effects of these complex refractive indices on: 1. Heat absorbed by water wall and secondary superheater from combustion chamber gases (radiation, convection and total); 2. Combustion chamber exit temperature and 3. Heat flux distribution on furnace walls were presented.

Among the others, the following conclusions are drawn. Soot and alumina were compared for 25 μm mean particle diameter, and it was found that complex refractive index of the soot gives a higher heat transfer to the sink surfaces and a lower gas temperature at the furnace exit than the alumina complex refractive index. The comparison of complex refractive index for simulated ash and for soot, for 5 μm mean particle diameter, shows that the soot complex refractive index gives a higher heat flux to the water walls and lower gas temperature at furnace exit than the complex refractive index for simulated ash. The real value of the complex refractive index for ash material in pulverized-coal-fired boiler would be somewhere between the values given for soot and alumina. The mathematical model given here is believed to be widely applicable for the analyses of furnace combustion chambers.

TR9700152

THERMAL RADIATION IN A PASSIVE CONTAINMENT COOLING SYSTEM BY NATURAL AIR CONVECTION

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ABSTRACT

The Karlsruhe Research Center und the University Karlsruhe have proposed a new containment concept for future pressurized water reactors. This containment should ensure that it remains intact even in severe core meltdown accidents and the decay heat can be removed in a passive way by natural air convection and by thermal radiation.

To determine the coolability limit of such a passive containment cooling system, experimental investigations are performed in the PASCO (acronym for *passive containment cooling*) test facility of the Karlsruhe Research Center. By these experiments different effects, e.g. the effect of the heated wall temperture and the wall emissivity, on heat transfer are studied. Moreover, a data base is provided for validating advanced multi-dimensional computer codes.

In addition to the experimental work, numerical calculations are performed by using the three-dimensional computer code FLUTAN to simulate flow conditions and heat transfer behaviour in the PASCO test channel, an one-sided heated rectangular flow channel. Even though the FLUTAN code was successfully applied to many complex thermalhydraulic problems, it did not contain radiative heat transfer. To extend the application of the FLUTAN code to the PASCO problem, a radiation model is developed with the following main features:

- Radiatively non-participating fluids, grey and diffuse wall surfaces.
- Net radiation method for enclosures.
- Analytical methods for view factor calculation.
- Macro-element method for improving numerical efficiency.

This radiation model is implemented in the FLUTAN code and numerical calculations are performed. The numerical results agree well with the experimental data concerning the distribution of the air temperature and the surface wall temperature. For high wall emissivity thermal radiation enhances the entire heat transfer of natural air convection significantly, even at low temperature of the heated wall. Further research works are underway to develop heat transfer correlations of natural air convection coupled with thermal radiation in non-uniformly heated, rectangular vertical channels.

Abstract submitted to the "International Symposium on Radiative Heat Transfer", 14-18 August, 1995, Kusadasi, Turkey

THERMAL SIMULATION OF A GLASS PANEL SUBJECTED TO A FIRE. RADIATIVE AND CONDUCTIVE MODELIZATION OF THE SEMI-TRANSPARENT MEDIUM.

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This paper presents a study of the modelization of the thermal behaviour of glass used for windows in buildings subjected to the typical solicitation of an accidental fire. The manufacturers of this glass are concerned about predicting its behaviour in the kind of difficult conditions which generally lead to its mechanical destruction, given that glass breaks when subjected to large, rapid temperature variations. Safety standards require that sheet glass resist for a certain length of time, to enable the evacuation of people inside a burning building.

With the model we have constructed it is possible to follow, over a period of time the thermal state of a glass sheet subjected to a solicitation which is representative of a fire situation. Radiation data are processed with the P1 method, transfer being taken as unidirectional, given the thickness of the glass. Conduction is represented by the heat equation, radiative and conductive transfers being coupled. A detailed representation is given of the boundaries of the mediums, radiative as well as conductive. The aim of this study is to bring out not only the influence of the thickness of the glass, but also its thermo-optic characterization, using a spectrum of nongray medium, in relation to the traditional opaque medium hypothesis. There is also to be an analysis of the influence of the optic properties of the surfaces, which are different for the two sides of the physical boundaries : those on the outside, facing the external conditions, and those on the inside of the glass. The results are given in the form of diagrams showing sensitivity to these hypotheses.

TR9700154

IDENTIFICATION OF SIZE AND STRUCTURE OF SOOT AGGLOMERATES AT THE EXHAUST OF DIESEL ENGINES

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ABSTRACT: Feasibility of multi-wavelength laser diagnostics to characterize the soot agglomerates structure at diesel engine exhaust is investigated. Normalized scattered intensities and dissymmetry ratios are obtained numerically for different soot agglomerates. Primary soot diameters considered are between 20 and 50 nm, and the number of primary spheres varies from 25 to 125. The results are obtained for incident radiation wavelength spectrum of 200 to 500 nm. From the preliminary analyses it is found that if the primary sphere diameter is estimated *a priori* from TEM pictures (or other means), measurement of spectral variation of dissymmetry ratios can be used in characterizing the morphology of the agglomerates accurately. It is concluded that a more general study, which includes multiple fractal dimensions for mono- or poly-dispersed agglomerates can easily be performed by extending the approach presented here.

PRELIMINARY STUDY ON AIR-FUEL MIXING AND COMBUSTION OF A DIVIDED-CHAMBER DIESEL ENGINE SYSTEM

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ABSTRACT: In recent years, numerous experimental studies were carried out in optically accessible closed vessel, model combustion chamber and rapid compression machines in order to understand the Diesel combustion process. The advantage of using these devices is to study the influence of a single parameter on the engine internal process and to have large optical access for non-intrusive optical measurement techniques. However, it is difficult to operate simultaneously at high ambient temperature and pressure and with air swirl typical of real engines. Therefore, optically accessible engines are used to overcome these intrinsic limitations, even though severe constructive modifications are need. In particular, measurement techniques such as laser doppler velocimetry (LDV), light extinction, Mie scattering, 2-D particle image velocimetry (PIV), laser induced incandescence (LII) and laser induced fluorescence (LIF) techniques require special design since the orthogonal optical accesses could influence negatively the engine behaviour.

In the present paper, an alternative way to investigate the combustion process with optical techniques which allows a realistic design is proposed. It consists of a divided- chamber with longitudinal and lateral optical accesses, connected to a flat piston engine that supplies air swirl and typical of both direct injection and prechamber diesel engines. This device allows to apply the optical techniques mentioned above and the direct cinematography and flame spectroscopy. Moreover, the internal processes can be reproduced using the new KIVA-3 developed by A. Amsden at Los Alamos National Laboratory, a computer program with block-structured mesh for complex geometry.

The present preliminary study aims at analysing experimentally and numerically the in-cylinder processes focusing the attention on two main aspects of Diesel combustion: i) air-fuel mixture preparation and ii) spatial distribution of soot temperature and concentration. High-speed direct cinematography at 8,000 frames/s was used to visualize the spray distortion

and to follow the entire Diesel combustion process. The appearance of flame luminosity was used to indicate the spatial region of the Diesel jet where the combustion starts and the temporal evolution of the combustion. The ignition start downstream the spray in the region where the fuel is well atomized and the flame expands rapidly filling up the chamber volume. This trend is confirmed by the computations implemented with a new droplet breakup model and turbulent mixing- controlled combustion model.

The computations confirm also the flame emissivity measurements carried out by multicolor pyrometry at the same crank angle. Spectral emissivity measurements, in the range 300 to 700 nm, were used to investigate more quantitatively the combustion phenomenon. In fact the chemical species such as OH and CH radicals as well as the soot temperature and concentration were estimated in the different locations of chamber volume.

TR9700156

SURFACE RADIATION EFFECTS ON NATURAL CONVECTION COOLING OF A DISCRETE HEAT SOURCE IN AN OPEN-TOP CAVITY

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ABSTRACT. The heat transfer performance of an electronic heat generating device mounted on one of the vertical conductive walls of a two-dimensional open-top cavity is modelled numerically. Natural convection in the fluid, radiation heat exchange between the surfaces of the cavity, and conduction in the vertical walls are considered. The results are obtained for air in a cavity of 100 mm height, 20 mm width and with 2 mm thick vertical walls. The imposed heat flux on the heating element is varied leading to a variation of the heat flux based Rayleigh number from 1.148×10^4 to 8.03×10^4. Walls with different values of thermal emissivity are considered in order to explore the effects of surface radiation. Initial results were obtained neglecting radiation. However, comparison of the numerical results with the experimental data highlighted the importance of this mode of heat transfer. This led to the inclusion of a radiative heat transfer model in the computations. Noticeable changes in the thermal and flow fields in the cavity are observed when the radiation is included. A reversed flow in the cavity with the formation of a recirculation zone in the proximity of the cold vertical wall is observed for the conjugate radiation-convection case. This is attributed to a rise in the temperature of the cold wall due to the radiation heat exchange with the heating device. This behaviour can not be predicted if only natural convection is considered. Hence, it was concluded that fully conjugate analysis, i.e. natural convection, radiation and conduction, must be considered in the numerical modelling of heat transfer from cavities with discrete heat sources for accurate prediction of heat transfer data and flow and thermal fields.

TR9700157

EFFECT OF AN EVOLVING AEROSOL CLOUD ON AN UPWARD RADIATIVE HEAT TRANSFER

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ABSTRACT

The present paper deals with radiative heat transfer through a dense aerosol cloud.
We explain here the theoretical basis of a numerical model. In this model we solve the radiative heat transfer equation which coefficients are calculated with respect to the aerosol optical properties (extinction and scattering coefficients). These optical properties are determined using the Mie or Rayleigh theory, depending on the aerosol size.
This model can be used in different cases, here we applied it to the later phase of an hypothetical severe Pressurized water Reactor (PWR) accident, in a Molten Core Concrete Interaction (MCCI) framework. We then show that the numerous aerosols generated during the concrete ablation by the corium melt have a significant effect on the radiative transfer in the reactor containment.
Indeed, we present an example of calculation using given aerosol size and concentration distributions which allow us to determine extinction and scattering coefficient profiles. Our instance does not exactly model any experiment, however the physical conditions are very close to the test L4 from the Advanced Containment Experiment (ACE) program.
We also provide a calculation with constant values (with respect to the position) for the extinction and scattering coefficients. This last study will then allow us to simplify the radiative transfer equation in our model and therefore shows the effect of such a hypothesis.

TR9700158

RADIATIVE AND CONVECTIVE HEAT TRANSFER IN CIRCULAR SECTORS

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ABSTRACT. The radiative and convective heat transfer in circular sectors is numerically investigated in this paper. The flow is assumed to be a steady and fully developed incompressible flow and the entrance effects are considered. The momentum method is applied to simulate the radiation of the fluid, which is nonscattering absorptive gas. The thermal boundary condition is a constant temperature on the wall. The control volume method is used to discrete the governing equations for flow, heat transfer, and radiation. The results show that the participation of radiation leads to the enhancement of heat transfer, but changes the behavior of the variation of the local Nusselt number along the axial direction. For pure forced convection, the local Nusselt number decreases monotonically from a large value at the entrance to an asymptotic value. However, for combined radiative and convective heat transfer, the local Nusselt number decreases until it reaches a minimum value at certain downstream locations and then increases again.

NUMERICAL SIMULATION FOR RADIANT GAS FLOWS IN COMPLEX STRUCTURES

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ABSTRACT: A new hybrid method is described for numerically solving radiative—convective heat transfer in complex structures. The simulated thermal installations can be combustion chambers or furnaces in which the obstructing walls are set.

In this paper, Hottel zone method has been greatly improved. The development include three parts. First, based on the analysis of uniform sampling theorem and thermal radiation, the Uniform Deterministic Discrete Method (UDDM) is presented for radiative heat transfer in complex structures with participating media. By uniform sampling versus random sampling in radiation, this new technique is superior to Monte Carlo in accuracy, convergence, speed and computer cost. In present paper it is applied to evaluate the direct exchange areas of zone method even using fine grid. Second, for energy matrix equations, the Principal Variable Correction Method is described together with its physical priciple analysis. By using this new approach instead of Newton—Raphson or Broyden iteration, the convergent solution can be achieved more fast and easily. finally, considering the combination of convective heat exchange, a two—level grid is used, one for zone method, the other for the Navier—Stokes finite—difference eqution of gas fluid flow.

KEYWORDS: thermal radiation, fluid flow, numerical method, Monte Carlo method.

TR9700160

Modelling of a solar receiver dedicated to LPG cracking for ethylene production.

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A large solar central receiver plant for the cracking of liquid petroleum gas (LPG) to produce 20,000 tone/yr ethylene has been designed. The solar power required for this receiver is more than 30 MW at design point. This receiver has an hexagonal cross section with 8 m each side and 8 m height. Two hundered forty cracking tubes, 7.3cm in diameter each, are distributed in parallel to the receiver walls. The solar energy is introduced through the top of this receiver.

The model of this receiver calculates the mode in which the concentrated radiation entering the receiver aperture is redistributed through radiative heat transfer between the various refracting and absorbing surfaces, and then calculates the heat fluxes on the reactor walls. These fluxes heat up the reacting gases and supply the enthalpy for the endothermic cracking reactions.

In a series of similar cases for radiation heat transfer calculations we used the zonal method where the internal surface of the receiver and external surface of the reactor tubes are divided into surface elements considered isothermal and equi-energetic. The dimensionality of the problem depends the number of zones considered. The computational time associated with formulating net radiative exchange in such a type of enclosure varies roughly with the cube of the number of zones into which the surface is divided. Therefore to treat, by zonal method, a receiver with hundereds reactor tubes, where each tube is considered a separately is an impossible task even if we were using the most powerful computer. And for reactor modelling, this accuracy can be superfluous.

In this case can be used successfully the classical concept of equivalent gray plane introduced by Hottel and Sarofim. According to this concept a row of tubes mounted parallel to a refractory wall which received the radiative heat from exterior can be replaced in calculations by an equivalent grey plane having that emissivity which is a full measure of the effects of tube spacing and of back wall.

Following this concept we considered the receiver with six walls having the equivalent emissivity as in Hottel and Serafim's model. Each of these equivalent walls are divided into a number of zones. In order to decrease the number of zones to a resonable dimensionality of the problem, we assumed that a few neighbouring tubes belong to the same zone. The height of this equivalent wall is divided into a few paralel regions, therefore each zone characterizes equal portion of the length of a group of few tubes.

The flux calculated on each zone following our previous model (see for example: A.Segal and M. Levy: Solar Chemical Heat Pipe in Closed Loop Operation: Mathematical Model and Experiments, Solar Energy, Vol 51, No.5, pp. 367-376) gives the possibility for evaluation of the flux on each segment from the lenght of each reactor tube. The fluxes on the reactor tube are used as an input to the endothermic reactions of LPG cracking for ethylene production. The interface between the radiative part of this model (into receiver enclosure) and its chemical part (inside the tube reactor) is done through the wall temperatures on each reactor segment. The chemical part generates a temperature profile on the reactor walls which is used as improved boundary conditions for the radiative part and a new heat flux calculation is generated. The calculation converges to a unique steady state solution and generates the final receiver wall temperatures, net heat flux profile, reactor wall temperature profile and various other parameters.

This model has been helpful in designing this receiver for better understanding of its properties. The computer program based on this model was run for a variety of flow conditions, feed composition, the catalyst activity, and presure. Using this model made it possible to establish optimal conditions for operating the receiver and to establishment of the optimal configuration of the solar field of heliostats required for this application.

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