Final Report**RADIATIVE TRANSFER THROUGH AN ARRAY
OF DISCRETE SURFACES****Grant No. DE-FG06-91ER14171**

**James R. Welty, Principal Investigator
Department of Mechanical Engineering
Oregon State University
Corvallis, OR 97331**

**RECEIVED
SEP 11 1995
OSTI**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

August 1, 1995

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

RADIATIVE TRANSPORT THROUGH AN ARRAY OF DISCRETE SURFACES

Final Report

Summary

This has been a collaborative research effort carried out jointly by Oregon State University (OSU) and Battelle, Pacific Northwest Laboratory (PNL). Emphasized herein will be the efforts of the Oregon State University team which were primarily experimental.

The aim of this research has been to examine how the transfer of radiant energy through a two-dimensional array of typical packing elements is affected by geometric variables (spacing, packing arrangement, and element shapes). The information resulting from this study will be relevant to a spectrum of applications including fibrous insulation, ceramic fabrics, and air heating solar receivers. Computational and experimental results will also be useful in establishing criteria for the valid application of participating media models to systems of discrete surfaces. Additional studies, related to the principal goal, were undertaken as the research effort progressed. These side-issues resulted in three out of the total of 12 publications that resulted from this effort. Collaboration between OSU and PNL has been interactive regarding the experimental and numerical modeling phases of this effort with the results of one group offering guidance to the other.

Accomplishments achieved during the course of this effort include the following: (1) a state-of-the-art bidirectional reflectometer was designed, constructed and operated, (2) measurements were made and the results characterized of the bidirectional reflectance of several materials, (3) it was demonstrated that there is a need for information on the full bidirectional reflectance distribution function (BDRF) to describe radiant interchange involving striated surfaces, and (4) validation of results using the two-dimensional Monte Carlo code, developed at PNL, was achieved and the code was used to extend the results of a classic geometric problem in the radiant heat transfer literature.

Discussions of each of the areas listed above will next be presented with reference to the publications that have resulted from this work. A complete list of papers that have been published, accepted, and submitted for publication is included along with copies or reprints.

Discussion of Research Accomplishments

Apparatus Development and Surface Property Characterizations

The initial proposal, submitted to DOE, included plans to pursue directly the experimental evaluation of radiant energy emerging from an array of discrete surfaces of specified geometry with a well characterized incident radiant beam.

Shortly after the initiation of this effort it became apparent that the literature contained virtually no information which adequately characterizes the surface properties of any material of interest. In particular, there is the common assumption - virtually universal - that, of the four angles important to the functional expression of bidirectional reflectance (the fundamental surface property for radiant energy characterization), all published data presume no dependence on the azimuthal angle of the incident beam.

As a result of this finding and the knowledge that Monte Carlo modeling - the approach being used by the PNL personnel - requires very precise and complete surface property characterization, it was clear that the capability for measuring BDRF would be required locally. Subsequently the literature concerning radiometric measurements was reviewed and an original design of an instrument evolved. The reflectometer that has been developed possesses flexibility of use and precision that are superior to any similar devices described in the literature. A description of this apparatus and its use in material characterization have been described by Zaworski et al (1993), and Zaworski et al (1994).

Extension of the Hottel Analysis for Radiant Exchange with Tube Rows

A means of evaluating geometric effects involving radiant exchange between two tube rows with a refractory back surface was published by H.C. Hottel approximately 60 years ago. Hottel's approach was an ingenious, complicated, and laborious graphical method. A graphical representation of his results for two tube rows (the only case he investigated) has appeared in virtually every heat transfer textbook published since that time.

At a national conference, during which a presentation was made describing the capability of our Monte Carlo approach, a member of the audience, a Babcock and Wilcox engineer, asked if we could duplicate the Hottel results (as described in the preceding paragraph). His company uses these results regularly in their design activities. The Monte Carlo approach that has been developed in this work is an excellent method for evaluating geometric effects involved in radiant transfer involving two-dimensional arrays. The Hottel problem is among the simplest such array

geometries and was readily amenable to solution. Subsequently our results for the Hottel problem were sent to the individual who had posed the question. In going through this exercise it became apparent that we could generalize these results to any number of tube rows and any sort of regular tube spacing. This became the subject of an M.S. thesis; the results have been submitted for journal publication (Qualey et al, 1995).

Experimental Validation of Monte Carlo Modeling Results

The initial goal of this research program was that of providing experimental confirmation of results obtained numerical using the cell-to-cell Monte Carlo approach of Drost and Welty (1992). Numerous discussions have taken place between the PNL and OSU groups as several problems with validation have been encountered. A good deal of iteration has occurred in the modeling effort as problems were identified through the experimental phase. There has never been serious question about the correctness of experimental results but there has been concern about the amount of data necessary to take and record, and the means of presenting it both for use in the Monte Carlo simulation effort and for publication.

Some early results comparing modeling to experimental results for simple geometries have been presented (Zaworski et al, 1993). These results were possible only after the experimental capability for acquiring BDRF information had been developed. Some significant features of these comparisons were presented by Palmer, Drost, and Welty (1993). A more complete validation study has recently been completed for the spatial distribution of light through a rectangular gap bounded by highly reflective, diffuse surfaces (Zaworski et al, 1995) with a number of important modeling considerations described. This is the paper which brings to closure the original objectives of this grant. The **Conclusions** section of this summary paper includes the following statements which are appropriate closing comments to this report:

"A principal result of this work is that the inclusion of realistic surface properties in a Monte Carlo radiation simulation is not so simple an undertaking as one might believe *a priori*. When the surfaces in question display behavior that is not purely diffuse, then the problem of accounting for all of the functional variations in surface properties becomes formidable. It is also apparent that the assumption of diffuse-gray surfaces may yield results which are grossly in error. Some techniques for handling real surface properties have been attempted with reasonable success.

The Monte Carlo simulations successfully reproduced the experimental distribution of intensities in most cases for the simple gap geometry with diffuse reflecting surfaces. The only cases for which there were

significant differences between the simulation and experiment were those in which the incident beam was at a low angle relative to the gap surfaces. Problems would be expected under these circumstances, because the BDRF in this region is obtained almost entirely by extrapolation."

Publications

Drost, M.K. and J.R. Welty, 1992, "Monte Carlo Simulation of Radiation Heat Transfer in Arrays of Fixed Discrete Surfaces Using Cell-to-Cell Photon Transport," *Developments in Radiative Heat Transfer*, American Society of Mechanical Engineers, New York, NY

Drost, M.K., B.J. Palmer and J.R. Welty, 1993, "Aspects of Radiation Heat Transfer in Arrays of Fixed Discrete Surfaces," Proceedings of the Eleventh Symposium on Energy Engineering Sciences, U.S. DOE Report CONF-9305134, Argonne National Laboratory, Argonne, IL

Zaworski, J.R., J.R. Welty and M.K. Drost, 1993, "Measurement Techniques for Bidirectional Reflectance of Engineering Materials," Proceedings of the Eleventh Symposium on Energy Engineering Sciences, U.S. DOE Report CONF-9305134, Argonne National Laboratory, Argonne, IL

Drost, M.K., B.J. Palmer and J.R. Welty, 1993, "Aspects of Radiation Heat Transfer in Arrays of Fixed Discrete Surfaces," presented at the ASME/AIChE National Heat Transfer Conference, Atlanta, GA; published in *Radiative Heat Transfer - Theory and Applications*, ASME HTD-Vol 244, A.M. Smith and S.H. Chan, eds

Zaworski, J.R., J.R. Welty, M.K. Drost and B.J. Palmer, 1993, "Experimental Validation of a Monte Carlo Model for Radiative Heat Transfer," presented at the ASME/AIChE National Heat Transfer Conference, Atlanta, GA; published in *Radiative Heat Transfer - Theory and Applications*, ASME HTD-Vol 244, A.M. Smith and S.H. Chan, eds

Chaomei, Lo, B.J. Palmer, M.K. Drost and J.R. Welty, 1995, "Incorporation of Polarization Effects in Monte Carlo Simulations of Radiative Heat Transfer," *Numerical Heat Transfer, Part A*, 27, 129-142

Palmer, B.J., M.K. Drost and J.R. Welty, 1994, "Monte Carlo Simulation of Radiation Heat Transfer in Arrays of Fixed Discrete Surfaces Using Cell-to-Cell Photon Transport," *International Journal of Heat and Mass Transfer*, to appear

Palmer, B.J., M.K. Drost and J.R. Welty, 1994, "Comparison of the Equation of Transfer with Simulations on Large Arrays of Cylindrical Reflector Elements," submitted to the *ASME Journal of Heat Transfer*

Zaworski, J.R., J.R. Welty and M.K. Drost, 1994, "Measurement and Use of Bidirectional Reflectance," submitted for publication in the *International Journal of Heat and Mass Transfer*

Qualey, D.L., J.R. Welty and M.K. Drost, 1995, "A Monte Carlo Simulation of Radiation Heat Transfer From an Infinite Plate to Parallel Rows of Infinitely Long Tubes - Hottel Extended," submitted to Numerical Heat Transfer

Antoniak, Z.I., B.J. Palmer, M.K. Drost and J.R. Welty, 1994, "Parametric Study of Radiative Heat Transfer in Arrays of Fixed Discrete Surfaces," submitted to the ASME Journal of Heat Transfer

Zaworski, J.R., J.R. Welty, B.J. Palmer and M.K. Drost, 1995 "Comparison of Experiment with Monte Carlo Simulations on a Reflective Gap Using a Detailed Surface Properties Model," submitted to the ASME Journal of Heat Transfer

APPENDICES