

PORE-LEVEL NUMERICAL STUDY OF COUPLED CONDUCTION-RADIATION HEAT TRANSFER IN FOAMS

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PORE-LEVEL NUMERICAL STUDY OF COUPLED CONDUCTION-RADIATION HEAT TRANSFER IN FOAMS

by

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CERTIFICATE

I am satisfied that the thesis entitled “**PORE-LEVEL NUMERICAL STUDY OF COUPLED CONDUCTION-RADIATION HEAT TRANSFER IN FOAMS**” presented by **Mr. ABHISHEK SIT** is worthy of the consideration for the award of the degree of **DOCTOR OF PHILOSOPHY** and is a record of the original bonafide research work carried out by him under my guidance and supervision, and the results contained in it have not been submitted in part or full to any other university or institute for award of any degree/diploma.

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ABSTRACT

Closed-cell polymer foams are increasingly gaining interest in building industry, thanks to their optimal balance of thermal and structural properties, and their potential insulation capabilities. Their low effective thermal conductivity (ETC) is one of the key performance indicators which make them apt for building insulation. Heat transfer within such foams is primarily driven by a combination of conduction and radiation. The present work aims to investigate the coupled conduction-radiation heat transfer within these polymer foams and study the relation between the cellular morphology and the effective thermal conductivity of these foams. A numerical model based on coupled Monte Carlo–Finite Volume method is developed to simulate the multimode heat transfer at the pore scale, in order to predict the effective thermal conductivity. The in-house developed Monte Carlo code used is an improved version of a general collision based Monte Carlo formulation capable of solving radiative transport in a multiphase medium having different radiative properties and optical properties for each phase. The thesis works begins with the development of a one-dimensional heat transfer model formulated using multiphase approach (MPA) followed by extension of the model to three-dimensional geometries. For the pore-scale simulations, three-dimensional representative foam structures based on Cubic and Kelvin unit cells are computationally generated. A comparison with experimental ETC measurements on real polymer foams validates the numerical framework's performance. Subsequently, the model is employed to conduct a study of the influence of various foam morphology parameters such as porosity, cell size, foam thickness and wall thickness on the ETC of the foams.

Due to the high porosity of polymer insulation foams, radiation contribution can become significant along with the other heat transfer modes. Describing the radiative behavior inside these foams require the knowledge of the radiative properties. Thus, a parameter identification method based on coupled Monte Carlo–Particle Swarm Optimization (PSO) algorithm is developed to predict the spectral radiative properties namely transport extinction coefficient and scattering albedo using experimentally measured spectral transmittances across the wavelength range 2.0–16.7 μm . The parameter identification method works by comparing experimental transmittance measurements obtained for several wavelengths for a given set of sample thicknesses with numerical transmittances stemming from a numerical model for the corresponding wavelengths and sample thicknesses used in the experiment. The Monte Carlo

method is employed for inverse radiative analysis to obtain the numerical transmittances and PSO is used to identify the unknown radiative properties. The PSO with adaptive weighted delay velocity is implemented to prevent premature convergence and local trapping and ensure unique solution. The spectral hemispherical transmittances are measured on three cylindrical samples each for expanded polystyrene and polyethylene foams using Fourier Transform Infrared spectrometer. A transport approximation is used to simplify the radiative transfer equation (RTE) which expresses the RTE similar to an isotropic scattering case. The predicted radiative properties revealed that these foams are strongly dependent on wavelength and have a highly scattering nature.

Keywords: Closed-cell foams; coupled conduction-radiation; effective thermal conductivity; Monte Carlo simulation; OpenMPI parallelization; Particle Swarm Optimization; Hot Disk System; spectral radiative properties

सार

थर्मल और संरचनात्मक गुणों के अपने इष्टतम संतुलन और उनकी संभावित इन्सुलेशन क्षमताओं के कारण क्लोज-सेल पॉलीमर फोम निर्माण उद्योग में तेजी से दिलचस्पी ले रहे हैं। उनकी कम प्रभावी तापीय चालकता (ईटीसी) प्रमुख प्रदर्शन संकेतकों में से एक है जो उन्हें इन्सुलेशन के निर्माण के लिए उपयुक्त बनाती है। इस तरह के फोम के भीतर गर्मी हस्तांतरण मुख्य रूप से चालन और विकिरण के संयोजन से संचालित होता है। वर्तमान कार्य का उद्देश्य इन बहुलक फोमों के भीतर युग्मित चालन-विकिरण गर्मी हस्तांतरण की जांच करना और सेलुलर आकृति विज्ञान और इन फोमों की प्रभावी तापीय चालकता के बीच संबंध का अध्ययन करना है। प्रभावी तापीय चालकता की भविष्यवाणी करने के लिए, ताकना पैमाने पर मल्टीमोड हीट ट्रांसफर को अनुकरण करने के लिए युग्मित मोंटे कार्लो-परिमित वॉल्यूम विधि पर आधारित एक संख्यात्मक मॉडल विकसित किया गया है। इन-हाउस विकसित मोंटे कार्लो कोड का उपयोग सामान्य टक्कर आधारित मोंटे कार्लो फॉर्मूलेशन का एक उन्नत संस्करण है, जो प्रत्येक चरण के लिए विभिन्न विकिरण गुणों और ऑप्टिकल गुणों वाले मल्टीफ़ेज़ माध्यम में विकिरण परिवहन को हल करने में सक्षम है। थीसिस कार्य बहु-चरण दृष्टिकोण (एमपीए) का उपयोग करके तैयार किए गए एक-आयामी गर्मी हस्तांतरण मॉडल के विकास के साथ शुरू होता है, जिसके बाद मॉडल को तीन-आयामी ज्यामिति में विस्तारित किया जाता है। पोर-स्केल सिमुलेशन के लिए, घन और केल्विन इकाई कोशिकाओं पर आधारित त्रि-आयामी प्रतिनिधि फोम संरचनाएं कम्प्यूटेशनल रूप से उत्पन्न होती हैं। वास्तविक बहुलक फोम पर प्रायोगिक ईटीसी मापन के साथ तुलना संख्यात्मक ढांचे के प्रदर्शन को मान्य करती है। इसके बाद, मॉडल को फोम के ईटीसी पर संरंध्रता, सेल आकार, फोम मोटाई और दीवार की मोटाई जैसे विभिन्न फोम आकारिकी मापदंडों के प्रभाव का अध्ययन करने के लिए नियोजित किया गया है।

बहुलक इन्सुलेशन फोम की उच्च संरंध्रता के कारण, अन्य गर्मी हस्तांतरण मोड के साथ-साथ विकिरण योगदान महत्वपूर्ण हो सकता है। इन झागों के अंदर विकिरण संबंधी व्यवहार का वर्णन करने के लिए विकिरण संबंधी गुणों के ज्ञान की आवश्यकता होती है। इस प्रकार, युग्मित मोंटे कार्लो-पार्टिकल स्वार्म ऑप्टिमाइजेशन (पीएसओ) एल्गोरिथ्म पर आधारित एक पैरामीटर पहचान पद्धति को वर्णक्रमीय विकिरण गुणों की भविष्यवाणी करने के लिए विकसित किया गया है, जैसे कि वेवलेंथ रेंज 2.0-16.7 माइक्रोन में प्रयोगात्मक रूप से मापा वर्णक्रमीय संप्रेषण का उपयोग करते हुए परिवहन विलोपन गुणांक और बिखरने वाले अल्बेडो। पैरामीटर पहचान पद्धति प्रयोग में प्रयुक्त संबंधित तरंग दैर्ध्य और नमूना

मोटाई के लिए एक संख्यात्मक मॉडल से उत्पन्न होने वाले संख्यात्मक संप्रेषण के साथ नमूना मोटाई के दिए गए सेट के लिए कई तरंग दैर्ध्य के लिए प्राप्त प्रायोगिक संप्रेषण माप की तुलना करके काम करती है। संख्यात्मक संप्रेषण प्राप्त करने के लिए व्युत्क्रम विकिरण विश्लेषण के लिए मोंटे कार्लो पद्धति कार्यरत है और अज्ञात विकिरण गुणों की पहचान करने के लिए PSO का उपयोग किया जाता है। समयपूर्व अभिसरण और स्थानीय ट्रेपिंग को रोकने और अद्वितीय समाधान सुनिश्चित करने के लिए अनुकूली भारित विलंब वेग के साथ पीएसओ लागू किया गया है। फूरियर ट्रांसफॉर्म इन्फ्रारेड स्पेक्ट्रोमीटर का उपयोग करके विस्तारित पॉलीस्टाइनिन और पॉलीइथाइलीन फोम के लिए प्रत्येक तीन बेलनाकार नमूनों पर वर्णक्रमीय गोलार्ध संप्रेषण मापा जाता है। रेडिएटिव ट्रांसफर समीकरण (आरटीई) को सरल बनाने के लिए एक परिवहन सन्निकटन का उपयोग किया जाता है जो आरटीई को आइसोट्रोपिक स्कैटरिंग केस के समान व्यक्त करता है। अनुमानित विकिरण गुणों से पता चला है कि ये फोम तरंग दैर्ध्य पर दृढ़ता से निर्भर हैं और अत्यधिक बिखरने वाली प्रकृति हैं।

मुख्य शब्द: बंद सेल फोम; युग्मित चालन-विकिरण; प्रभावी तापीय चालकता; मोंटे कार्लो सिमुलेशन; ओपनएमपीआई समांतरता; कण झुंड अनुकूलन; हॉट डिस्क सिस्टम; वर्णक्रमीय विकिरण गुण

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NOMENCLATURE

G	incident radiation (W/m ²)
I	radiation intensity (W/m ² sr)
k	thermal conductivity (W/m K)
$\hat{n}$	unit normal vector
$\hat{t}$	unit tangential vector
$\overrightarrow{q_R}$	radiative heat flux (W/m ²)
q_{cond}	conductive heat flux (W/m ²)
T	temperature
r	position vector
x, y, z	cartesian coordinates
n	refractive index
E	radiative emissive power
P	probability density function
R	random number
T	transmittance
N	conduction-radiation parameter $\left(\frac{\kappa\beta}{4\sigma T^3}\right)$

GREEK SYMBOLS

λ	wavelength (μm)
β	extinction coefficient (m ⁻¹)
σ_s	scattering coefficient (m ⁻¹)
σ	Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$)
κ	absorption coefficient (m ⁻¹)
ω	scattering albedo
Ω	solid angle (sr)
ϵ	emissivity
Φ	scattering phase function
θ	zenith or polar angle
ϕ	azimuthal angle
ρ	reflectivity

τ	optical thickness
ψ	non-dimensional radiative flux

ABBREVIATIONS

HPA	Homogeneous Phase Approach
MPA	Multiphase Approach
MCM	Monte Carlo Method
FVM	Finite Volume Method
ETC	Effective Thermal Conductivity
MIR	Mid-Infrared Region
RTE	Radiative Transfer Equation
PSO	Particle Swarm Optimization
RNG	Random Number Generator
LCG	Linear Congruential Generator
PS	Polystyrene
PU	Polyurethane
PE	Polyethylene
EPS	Expanded Polystyrene
SPMD	Single Program Multiple Data