Deservedly, Chang-Lin Tien is recognized as one of the world’s premier researchers in the fields of heat and mass transfer and thermofluids sciences. Tien’s research activities extended to biological and multiphase systems, superlattices, and porous silicon. He achieved a remarkably distinguished record, both as a scientist and educator. Tien made substantial contributions in numerous areas, including heat and mass transfer, fluid mechanics, computational science, and engineering. His pioneering work was heralded internationally by experimentalists and theoreticians alike in great part owing to his ingenious, ground-breaking efforts in modeling. Tien’s interests covered analytical, experimental, and computational analyses of numerous physical systems. Several international researchers, themselves of considerable renown and whose interests coincided with Tien’s, have paid glowing tribute to his preeminent body of work.

Over his illustrious career, Tien received a plethora of awards. One of these awards, presented at the ASME International Mechanical Engineering Exposition and Congress, resulted from a 1981 paper, “Boundary and Inertia Effects of Flow and Heat Transfer in Porous Media” [1]. The award recognizes those authors and their papers that have significantly contributed to technology and the science of heat transfer over a substantial number of years. The paper analyzed the effects of a solid boundary and inertial forces on the flow and heat transfer in porous media, and was the first such comprehensive paper in this area to utilize the local volume-averaging technique to establish a proper set of governing equations.

Tien contributed to the porous media modeling in collaboration with other researchers. The areas of development included non-Darcian effects, thermal dispersion, multiphase transport models in porous media, porous silicon, and convective and radiative heat transfer in porous media. The importance of porous media in a variety of different industrial applications, such as packed-bed chemical reactors, petroleum reservoirs, building thermal insulation, and geothermal operations, led to extensive investigations in these areas. Most of the existing studies in the literature
dealt primarily with the mathematical simplifications based on Darcy's law, which neglects the effects of the solid boundary, inertial forces, and variable porosity on flow through porous media, till the pioneering work of Vafai and Tien [1] presented for the first time an in-depth analysis of boundary and inertia effects. The authors developed the governing equations for fluid flow through a porous media using the local volume-averaging technique. The results of this study allowed a simple characterization scheme for interpreting the applicability of Darcy's law to various problems of flow and heat transfer in porous media. In this work, the concept of momentum boundary layer and introduction of proper averaging volume for interpreting the results within a momentum boundary layer were presented for the first time.

The effects of the presence of a solid boundary and inertial forces on the transient mass transfer in porous media were studied by Vafai and Tien [2] for the first time in the literature. Particular emphasis was placed on mass transfer through the porous medium near an impermeable boundary. The local volume-averaging technique was implemented to establish the governing equations. A transient mass transfer experiment was conducted in conjunction with the numerical solution to demonstrate the boundary and inertia effects on mass transfer. Hong et al. [3] presented an analytical study on the non-Darcian effects on natural convection from a vertical plate embedded in a high-porosity medium. The results showed that the boundary and inertia effects had a significant influence on the velocity profiles and surface heat transfer rate. The results also showed that the boundary effect became more noticeable in the region close to the leading edge of the heated plate, while the inertia effect increased with downstream locations on a heated plate.

In many applications, such as in packed-bed catalytic reactors, the porous media is bounded, the fluid velocity is high, and the porosity is variable; therefore, it is important to investigate the solid boundary, inertia, and the variable porosity effects on the convective flow and heat transfer within the porous medium. The variable porosity close to an impermeable solid boundary leads to a number of important effects, such as flow maldistribution and channeling, which refers to the occurrence of a maximum velocity in a region close to an external boundary. The region close to an external boundary is of particular interest since many significant parameters, such as the heat flux at the boundary, are closely involved in that region. Most of the heat transfer investigations in packed beds did not consider the effects of boundary and variable porosity. Vafai et al. [4] conducted a comprehensive study both experimentally and numerically on the effects of a solid impermeable boundary and variable porosity on forced convection in a porous medium. The local volume-averaging technique was utilized to develop the governing equations, which incorporated the boundary and variable porosity effects on heat transfer. The experimental results were found to be in good agreement with the theoretical simulation, taking into account the variable porosity effects. Comparison between the numerical and the experimental results illustrated the significance of the boundary and variable porosity effects on the fluid flow and heat transfer in a variable porosity medium. White and Tien [5] obtained a closed-form solution based on the work of Vafai [6] using an exponential porosity distribution, which is a typical distribution in packed beds. The predicted velocity
profiles showed the most important features of the flow channeling. Non-Darcian flow and heat and mass transfer in catalytic packed-bed reactors were analyzed by Hunt and Tien [7]. Traditional models of transport in packed beds assume that the velocity across the reactor is uniform. Hunt and Tien [7] carried out a non-Darcian analysis incorporating the porosity variation close to the wall. The corresponding heat transfer solutions incorporated the wall-temperature boundary condition to predict cooling rates in the presence of chemical reactions. The results from Hunt and Tien [7] were in agreement with the experimental data.

Microsphere insulation, which represents a special type of packed bed, is basically a stagnant agglomerate of small unconsolidated spherical particles. Determination of the thermal characteristics of such beds, especially the conduction contribution, is of special interest to researchers. Tien and Vafai [8] accommodated the random arrangement of solid particles by assuming the packed bed is composed of various different packing structures randomly dispersed throughout the bed.

Thermal dispersion represents an important topic in packed beds, which relates to the mixing and recirculation of local fluid streams as the fluid flows through tortuous paths offered by the solid particles. Hunt and Tien [9] conducted an experimental study to investigate non-Darcian flow and heat transfer in high-porosity fibrous media. The observed enhancement was mainly attributed to dispersion, a non-Darcian phenomenon describing the mixing that occurs when the fluid moves past the solid particles. The effect of high flow rate, near-wall porosity variation, solid boundary shear, and thermal dispersion on the fluid flow and heat transfer in packed beds was studied by Hunt and Tien [10]. The non-Darcian formulation was used to predict the heat transfer rates in cylindrical packed beds, such as chemical reactors. The results of their study agreed with the experimental chemical reactor data. Transverse dispersion in packed-sphere beds was studied theoretically by Kuo and Tien [11]. They showed that the dispersion coefficient was proportional to the square of the dimensionless distance from the wall. A damping function was proposed in this study to account for the dispersion reduction near the wall. Natural and forced convection boundary-layer flow and heat transfer in packed beds were studied by Tien and Hunt [12], taking into account non-Darcian effects, such as the solid boundary resistance, high flow rate inertia losses, near-wall porosity variation, and thermal dispersion. These effects were found to significantly alter velocity and temperature profiles in boundary-layer and confined flows. Diffusion and dispersion regimes for boundary-layer flow in a porous medium were also analyzed by Hunt and Tien [13].

The buoyancy-induced flow in fluid-saturated porous media has been a major topic of many studies during the past three decades. This is due to its importance in many industrial applications, such as thermal insulation engineering, water migration in geothermal reservoirs, underground spreading of chemical waste, nuclear waste repository, and enhanced recovery of petroleum reservoirs. Most of the previous investigations included natural convection in confined enclosures, and consideration of the end effects on the fluid flow and heat transfer was limited. Bejan and Tien [14] developed an approximate analytical solution of the fluid flow and heat transfer in a shallow porous cavity with vertical, permeable walls subject to an end-
to-end temperature difference. Haajizadeh and Tien [15] studied the same problem originally considered by Bejan and Tien [14]. In this work, the asymptotic solutions for a shallow open cavity, including the numerical and experimental results, were presented. Tien and Hong [16] analyzed natural convection in shallow open cavities with clear and porous media. For confined enclosures, combined natural and forced convection in a horizontal porous channel was studied by Haajizadeh and Tien [17]. The effect of internal heat generation on natural convection in a vertical porous enclosure was also studied by Haajizadeh et al. [18].

Burns et al. [19] analyzed analytically convective heat transfer through porous insulation in a vertical slot. A simple analytical formula for calculating the heat transfer was presented, after obtaining a matching coefficient by comparison with numerical solutions. Both free and forced convection, simulating wall leakage in common building structures, were considered. Numerical results for the case of no wall leakage were in good agreement with those presently available. It was shown that, for appreciable wall leakage, the dominant mode of heat transfer was due to the enthalpy change of the transferred fluid as it was blown through the enclosure. Burns and Tien [20] conducted an analytical investigation of natural convection in porous media completely enclosed by concentric spheres and horizontal cylinders. The steady, two-dimensional problem was solved by the method of finite differences and the method of regular perturbations. The variations of the overall heat transfer with the modified Rayleigh number, the nondimensional external heat transfer coefficient, and the radius ratio were assessed in their study. Results indicated that a maximum value of the heat transfer occurred for the spherical and cylindrical geometries dependent solely upon the radius ratio for each geometry. The flow field was examined and compared for the two geometries. An interesting feature was manifested by the occurrence of a relatively stagnant and stable cold region at the bottom of the enclosure if the inner bounding surface was considered to be heated, thus shifting the center of the gross circulation from the horizontal.

Tien also made significant contributions in the area of film condensation in a porous medium. Flik and Tien [21] performed an approximate analysis for general film condensation transients. Their analysis revealed that general film condensation transients are governed by the propagation of a kinematic wave. Closed-form solutions for step changes in the body force, vapor shear, and wall temperature for a laminar film and for step changes in body force and wall temperature for a film within a porous medium were obtained. The effects of surface tension on film condensation in a porous medium were analyzed by Majumdar and Tien [22]. In the process of film condensation in a porous medium, the thermodynamics of phase equilibrium require the existence of a two-phase zone between the liquid and vapor regions. In the two-phase zone, solutions of the conservation equations indicated a boundary-layer profile of the capillary pressure. The liquid zone was analyzed by using three models, which assume either slip or no slip at the wall and Darcy velocity or no shear at the interface with the two-phase zone. Peterson and Tien [23] presented an analysis to show that a miniature wet-bulb/dry-bulb probe could provide point measurement of noncondensable gas concentrations in condensing or evaporating systems. The
probe consisted of a liquid-soaked porous sphere \( \geq 0.5 \text{ mm} \) in diameter with a fine-gage thermocouple embedded at its center. Measurements of only the total pressure and wet-bulb temperature were needed to determine the local gas concentration in most systems.

Porous silicon has generated a significant amount of interest due to its potential application to silicon optoelectronic devices as a result of its extraordinary material properties. Porous silicon is made by dissolving a bulk silicon wafer in an electrochemical cell containing a hydrogen fluoride solution. Porous silicon is composed of fibrous silicon structures of nanometer dimensions. Tien and coworkers [24–27] have made a number of contributions in the porous silicon area. Hipwell and Tien [24] proposed five level systems to model the short time-scale radiative transfer in light-emitting porous silicon. The governing equations were derived for various energy levels. The model was applied to picosecond differential transmission measurements made on porous silicon. A picture of short time-scale carrier dynamics was drawn considering the unique properties of confinement, high surface-to-volume ratio, and disorder on several length scales. The dual-beam picosecond continuum technique for measurement of short time-scale optical properties of novel materials was presented by Hipwell and Tien [25]. The dual-beam approach was proposed to allow simultaneous measurement of sample properties in both the excited and steady states. Differential transmission measurements were made by Hipwell et al. [26] to characterize the short time-scale optical properties of p-type light-emitting porous silicon. Aged and freshly etched samples were used to determine the impact of aging on nonlinear optical properties. Hipwell and Tien [27] applied fractal percolation theory to examine the impact of anomalous diffusion in short time-scale applications of random media. They displayed the existence of three heat transfer regimes corresponding to transport over the basic percolation unit (particle), the fractal cluster, and the homogeneous medium. Scaling was performed to determine the characteristic time scales of anomalous diffusion.

Tien extended his research to the application of external radiation heating in porous solid fuels. Park and Tien [28] reported that radiation absorption in gas-phase and natural convection play a significant role in gas-phase ignition of porous solid fuels exposed to an external radiation heating. A theoretical model for a transient one-dimensional analysis including radiation absorption and scattering by the fibrous structure of the fuel was developed. The results of this study show that the predicted ignition delay times were found to be in excellent agreement with experimental results. Moreover, a parametric study revealed that ignition under unfavorable conditions to attain a thermal runaway was induced mainly by radiation absorption in the gas phase.

The study of convection heat transfer in porous media has received considerable interest because of its wide applicability in geothermal energy technology, filtration processes, packed-bed reactors, and underground disposal of chemical and nuclear waste. At high temperatures, thermal radiation can be substantially affected by the heat transfer and temperature distribution of the participating fluid. Tien and Vafai [29] conducted a comprehensive review of the convective and radiative heat
transfer in porous media detailing the pertinent attributes in these areas.

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