

STOKES FLOW PAST A TWO-LAYERS HETEROGENEOUS POROUS SPHERE WITH THE EFFECT OF STRESS JUMP CONDITION: AN EXACT SOLUTION

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Key Words: Stokes flow; heterogeneous porous sphere; stress jump condition; Darcy-Brinkman equation

The flow past a porous sphere has extensive industrial and engineering applications, such as the flow of pulverized coals particulate during combustion, sedimentation of fine particulate suspensions, flow in porous beds etc. Several studies have been done about the flow past a porous body under different models and boundary conditions. The models used in their investigations can be divided into the following categories: (i) Adopting Darcy equation to describe the flow in porous media and Stokes equations to describe the flow in the free fluid with the continuity conditions of velocity and pressure at the interface or the Beavers-Joseph (BJ) interface conditions; (ii) Adopting the Darcy-Brinkman equation to describe the flow inside the porous region and Stokes equations to describe the flow in the free fluid region with interface conditions which are the continuity of velocity components and stresses at the interface or with the Ochoa-Tapia and Whitaker interface conditions, in which shearing stress jump at the interface is considered. However, most of researches just considered one-layer porous medium whether it was a porous sphere or a porous sphere containing a solid concentric spherical core or a concentric spherical cavity. P. D. Verma and B. S. Bhatt (1976) investigated the flow past a heterogeneous porous sphere with the Darcy model.

In this paper, a heterogeneous porous sphere containing two-layers porous medium of internal radius ' R_1 ' and external radius ' R_2 ' is considered, which is immersed in a uniform stream of velocity v . The internal porous region, the external porous region and the free fluid region are denoted by regions I, II and III respectively. Darcy-Brinkman equation is adopted to describe the flow in region I and region II separately and Stokes equations are adopted to describe the flow in region III. The continuity of the velocity components and stresses are taken at the interface between region I and region II. The continuity of the velocity components and normal stress and shearing stress jump conditions are taken at the interface between region II and region III. The exact flow solutions are derived. The expressions of the drag force on the surface of the sphere and the stream function for free fluid region, the internal porous region and the external porous region are determined. Moreover, the analytical solutions have been verified in some limiting cases. If the permeability in external region reaches zero, the current expression of drag will be identical with the expression for stokes flow past a solid sphere. If the internal radius R_1 approaches zero or the internal and external porous medium have the same physical properties, the current solutions will agree with the results of A. C. Srivastava and Neetu (2005) for flow past a homogeneous porous sphere. Furthermore, if the stress jump coefficient is zero and the permeability is small, the current expression of the drag on the sphere is identical with the expression deduced by Yu and Kaloni(1988). For the same reason, if the permeability in internal region approaches zero, the current solutions will agree with A. C. Srivastava and Neetu (2006) for stokes flow past a porous sphere with a solid core. If the permeability in the internal region reaches infinity, the current solutions agree with the results for flow past a porous spherical shell with a concentric spherical cavity under the continuity conditions of velocity components and stresses at the interface between porous shell and internal cavity. In addition, it is found that both the permeability and the stress jump coefficient have significant effects on the drag. The variation of drag with the permeability in internal and external regions for different inner to outer ratio (R_1/R_2) as well as for different stress jump coefficient is discussed. It is found that the drag increases with the decrease of the internal and external permeability and the stress jump coefficient.

TIME FRACTIONAL TRANSPORT MODEL FOR FLOW THROUGH TIGHT POROUS MEDIA

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Key Words: Shale, gas, tight porous rock, simulation, transport model

Modelling the flow of fluid through tight porous media, such as unconventional hydrocarbon reservoirs, is very challenging and it is a growing sector and must be addressed. Shale gas is found in such tight porous rocks which are characterized by nano-scale size porous networks with ultra-low permeability [1,2].

Here gas non-linear transport models for reservoir simulations of single-phase gas through homogeneous tight rocks, [3], is combined with a fractional calculus method, [4,5], to pose a new time-fractional advection-diffusion transport model [6,7] for the pressure field, $p = p(x, t)$,

$$\frac{\partial^\alpha p}{\partial t^\alpha} = \mathcal{L}(p) + R(x, t), \quad t > 0, \quad a \leq x \leq b; \quad 0 < \alpha < 1,$$

and with suitable initial and boundary conditions, where $\mathcal{L}(\cdot) \equiv \frac{\partial}{\partial x} \left(-U(\cdot) + K \frac{\partial}{\partial x} (\cdot) \right)$ is a second order differential operator, $\frac{\partial^\alpha}{\partial t^\alpha}$ is the Caputo fractional derivative of order α , R is an source term, and $b - a$ is the length of the reservoir. In these models, the apparent diffusivity is $K = K(x; p)$, and the apparent convective velocity is $U = U(x; p, p_x)$; thus either or both of K and U can be non-linear. We will analyse the solutions for different fractional order α , and compare the solutions with other models and against data where available.

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MODELLING THE EFFECT OF THE POROUS SUPPORT ON THE FLUX THROUGH ASYMMETRIC OXYGEN GAS SEPARATION MEMBRANES

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Key Words: Gas separation membranes, binary friction model, microstructure, computed tomography.

Oxygen Transport Membranes (OTM) represent a new technology for energy-efficient oxygen generation which can be used in low-pollutant power plants and oxygen generators or membrane reactors in the chemical industry and health care. The two competing demands of low ionic resistance of the functional separation membrane and high mechanical stability lead to an asymmetric design comprising of a thin membrane layer and a thicker porous support. However, the overall membrane performance is strongly affected by the microstructure of this support layer which prevented the use of the full potential of such a design in the past. The effect of the support on the flux performance has been thus studied applying the Binary Friction Model (BFM, including binary and Knudsen diffusion and viscous flow) for the support together with a modified Wagner equation for the dense membrane. The transport-relevant parameters describing the tape-cast porous medium with an average pore diameter of 6.3 μm were obtained by numerical diffusion and flow simulations based on micro computed tomography (μCT) data (Fig. 1). The resulting fluxes were found to be in good agreement with the experimental permeation tests. Different flow conditions (3-end with vacuum, 4-end with Ar sweep gas), assembly orientation, feed atmospheres (air/ O_2) were modelled and the effect of geometrical changes in the support (pore size, pore anisotropy, layer thicknesses) on the overall flux studied. Knudsen diffusion was found to dominate the transport process for small pore sizes ($\sim 2 \mu\text{m}$) in particular for the 3-end mode with the support on the permeate side being most pore size sensitive, whereas for the other configurations the viscous flow was of higher significance. For typical pressure conditions, the oxygen flux was found to be superior in the 3-end mode with the support on the permeate side as in this case the absence of a second gas in the substrate allows a fast transport of the permeate gas through the porous medium (Fig 2).

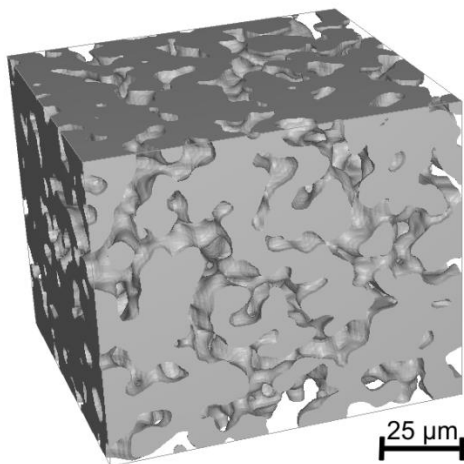


Figure 1 – Computed tomography (μCT) of tape cast support (cropped)

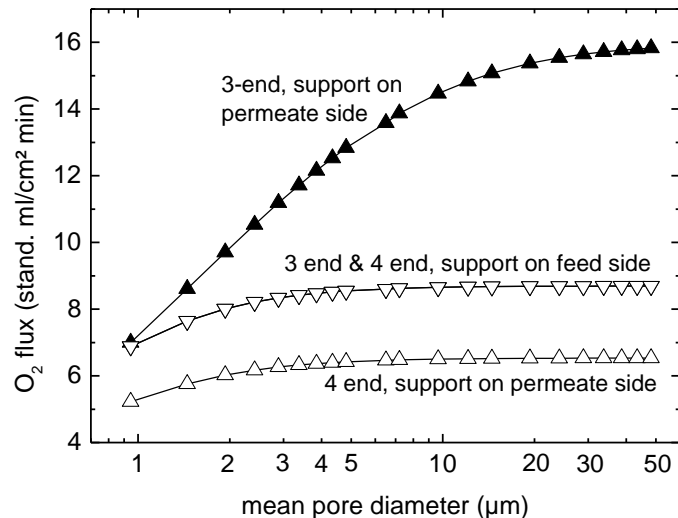


Figure 2 – Calculated O_2 flux through an asymmetric $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_{3-\square}$ (BSCF) membrane at 900°C for varying pore diameters in the support and different operation modes. Feed side: air (1bar), perm. side: O_2 ($p_{\text{O}_2}=73.5 \text{ mbar}$) and Ar (4 end, 927 mbar)

EXACT SOLUTION FOR VISCOUS FLUID FLOW IN POROUS MEDIA WITH MAGNETIC FIELD

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Keywords: Lorentz's force, Uniform velocity, Magnetic field, Bessel function, shear stress.

The steady flow of viscous, incompressible, conducting fluid flow past a spherical solid core embedded in another spherical porous medium is considered. The exact solution is obtained for the flow in the presence of transverse magnetic field. The considered fluid flow is governed by Brinkman equation in porous region and by Stokes equation in the fluid region with additional Lorentz's force due to applied magnetic field. The flows in the two regions are matched across the interface by assuming continuity of velocity and stress across the interface. Further, no-slip condition at the solid surface and uniform velocity far from the flow region are used. The solutions are obtained by similarity transformation method in terms of modified Bessel's functions. The expression for tangential shear stress, normal and tangential velocity is obtained. The results are demonstrated by graphs for various non-dimensional parameters. It is noticed that diffusion of the fluid into porous region is more as magnetic field strength is amplified. This shows the suppression of the flow in the presence of magnetic field. Also, the amplitude of the shearing stress intensifies with increase in the magnetic field strength and lessens with raise in porous parameter.

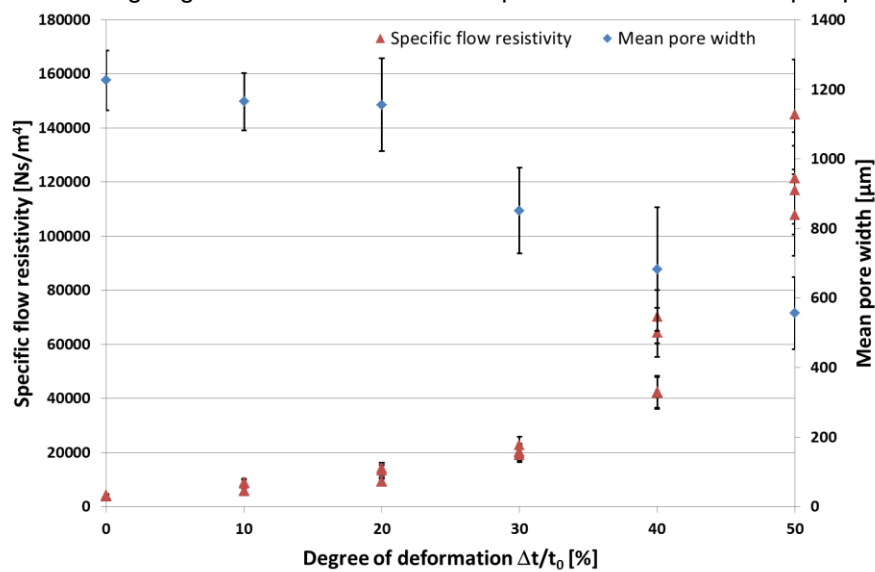
THE INFLUENCE OF COLD ROLLING ON THE PORE MORPHOLOGY AND FLOW RESISTIVITY OF POROUS ALUMINUM

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Key Words: cold rolling, X-ray tomography, flow-resistivity, porous aluminum, pore morphology

Materials with an open porosity are used in many applications, such as filters, acoustic absorbers or heat exchangers. For these applications the pore size and shape as well as the depending flow resistivity are important parameters and need to be adjusted for the specific case. The material parameters are usually defined by the manufacturing process and are therefore signature for different types of porous materials. In this study the porosity, pore shape and the depending flow resistivity of a given material are adjusted using a cold rolling process. The material chosen is a porous aluminum with a porosity of about 50% and relatively large pore, what allows to adjust pore size and porosity on large scale. The porous aluminum is produced using a salt infiltration technique and was received from “Exxentis”¹. To ensure a good deformability a technically pure aluminum was chosen for the porous plates. By deforming the porous aluminum in a rolling mill, the plates are elongated and the thickness is reduced. This causes a reduction of the porosity due to closing pores and an elongation of the pores in the rolling direction along with the material flow.

To characterize the initial porous structure and describe the structural evolution during the cold rolling three dimensional X-ray scans for various degrees of deformation were taken. To analyze pore size and pore shape a line segmentation technique was applied to two dimensional images that were extracted from the 3D reconstructions. The 2D images were extracted in image stacks parallel to the three main surfaces of the rolled plate (parallel and perpendicular to the rolling direction). It was observed that porosity and pore size are decreasing with an increasing degree of deformation and that the aspect ratio of the pores is increasing. Even though the pores are closing during the rolling process, the X-ray scans show an open porosity even for high degrees of deformation. These results were compared to the evolution of the flow resistivity. The flow resistivity was measured in three orientations mentioned above for the initial and rolled plates, using the alternative airflow method (Method B DIN EN 29035). The measured values were divided by the material thickness to obtain a specific flow resistivity for rolled plates with different thicknesses. The specific flow resistivity is decreasing with an increasing degree of deformation. It was possible to confirm the open porosity for high degrees of



deformation that was observed in the X-ray scans. This study shows that it is possible to adjust pore size, porosity and flow resistivity of porous aluminum using a cold rolling process. The flow resistivity, perpendicular to the rolled surface, and the mean pore width, in planes parallel to the rolled surface, for different degrees of deformation are shown in Figure 1.

Figure 1 – Flow resistivity and pore width for porous Aluminum after cold rolling

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EXPERIMENTAL RESEARCH ON INTERNAL CONVECTION HEAT TRANSFER OF SUPERCRITICAL PRESSURE CO₂ IN POROUS MEDIA

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Key Words: supercritical pressure CO₂, porous media, internal heat transfer coefficient.

The flow and heat transfer of fluids at supercritical pressure in porous media has attracted much attention due to its extensive applications, such as supercritical water-cooled nuclear reactor, CO₂ gas cooled reactor, transpiration cooling and supercritical CO₂ solar thermal power generation system. There are mainly two theories to describe convection heat transfer in porous media, i.e., the local thermal equilibrium model (LTE) and the local thermal non-equilibrium model (LTNE). Compared with LTE model, the LTNE model is a more detailed model that uses two energy equations to describe heat transport in the solid and fluid. The internal heat transfer coefficient is a key parameter for LTNE model which has been studied thoroughly and many correlations have been proposed. However, for the fluids at supercritical pressure, the thermophysical properties vary widely near the pseudo-critical point, which significantly impacts the internal convection heat transfer of the fluid flowing through the porous media. Therefore, we conducted an experimental study aiming to evaluate the internal convection heat transfer of supercritical pressure CO₂ in porous media. The experimental test section was designed with confining pressure to prevent the fluid from flowing through the gap between the sample and holder wall. The internal convection heat transfer coefficients between particles and CO₂ in the sintered bronze porous media with average diameters of 200 μm, 90 μm and 40 μm and porosities of 0.4 and 0.3 were determined experimentally by the single blow method. A Nusselt number correlation was developed that includes the influence of sharp variations of thermophysical properties of supercritical pressure CO₂.

MICRO-NANO SCALES FLOWING SIMULATION IN SHALE GAS

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Keywords: shale gas, transport mechanisms, pore network model, nano-scale flowing simulation, flowing characteristics

The storage space of shale reservoir is mainly composed of complicated nanoscale pore, in which the gas exists in the form of absorbed gas and free gas. Due to the complicated pore structure and various gas storage states, gas flowing in the pore space is affected by multiple transport mechanisms including adsorption, desorption, Darcy flow, slippage and diffusion, etc. Therefore, a comprehensive research on the effects of transport mechanisms on shale gas flow is the key to study the shale gas migration rule, evaluate production capacity, and make reasonable development plan. Firstly, according to the physical meanings and interactive relationships of transport mechanisms, the flowing mathematical model is established for the pure methane gas. Then, based on the pore network model, which takes both the geometrical morphology and topological structure of shale matrix pore space into consideration, the above flowing mathematical model is discretized to construct the corresponding pore network flowing numerical model. Finally, gas flowing simulation is carried out by solving the model. The impacts of various transport mechanisms on gas flowing in the process of shale gas development under different physical properties and pore pressures are studied, and the changes of gas flow mechanisms at different stages are also analyzed. The research results will contribute to the understanding of the gas transport rules in shale gas reservoir, improve seepage theory of this unconventional reservoir and provide a theoretical support for rational development plans.

EXPERIMENTAL INVESTIGATION OF COMBINED TRANSPIRATION AND JET COOLING OF SINTERED METAL POROUS STRUTS

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The scramjet combustion chamber provides the propulsion for hypersonic vehicle. The fuel is combusted in the chamber to generate thrust. The strut is used to inject fuel into the core of combustion chamber to enhance the mixing and the combustion. The mainstream in a scramjet combustion chamber is at supersonic velocity and high temperature. The tremendous aerodynamic heating will then cause ablation of the strut without adequate cooling. Therefore, effective thermal protection methods must be provided for the strut, especially for the leading edge. Transpiration cooling is one of the most effective cooling methods to protect surfaces at high heat flux conditions, and can effectively protect most part of the strut, but some ablation was found at the strut leading edge. Therefore, more effective cooling method is needed to protect the strut, especially the leading edge. Opposing jet cooling is an effective cooling method to protect the leading edge.

This paper describes a particular experimental study of cooling using both transpiration and opposing jet cooling to protect the strut. The strut material was sintered stainless steel with a micro-slit on the leading edge as shown in Fig. 1. The micro-slit width is about 0.1 mm through Linear Cutting. The influences of the micro-slit width and coolant injection pressure on the cooling effectiveness were studied. The effect of non-uniform injection pressures was also investigated. The results showed that the combined transpiration and opposing jet cooling can effectively protect the strut.

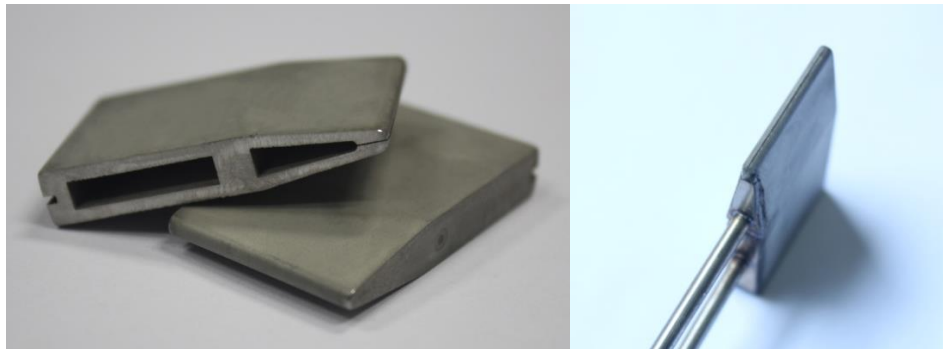


Figure 1 – Sintered metal porous struts with a micro-slit on the leading edge

RESERVOIR SIMULATIONS OF SHALE GAS IN TIGHT ROCKS USING A NON-LINEAR TRANSPORT MODEL WITH FULLY PRESSURE DEPENDENT MODEL PARAMETERS

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Key Words: Shale, gas, tight porous rock, simulation, transport model

A new source of energy has recently been discovered from unconventional hydrocarbon reservoirs, such as shale gas deposits. Shale gas is found in tight porous rocks which are characterised by nano-scale size porous networks with ultra-low permeability [1,2]. The modelling of transport through such tight porous media is very challenging because it is a relatively new discipline and not much is known but transport processes in them, and little data is available; but it is a growing sector and must be addressed. Here, we apply a recently developed non-linear gas transport model [3], to reservoir simulations of single-phase gas through homogeneous tight rocks. The transport model is an advection-diffusion partial differential equation for the pressure field, $p = p(x, t)$, in such reservoirs,

$$\frac{\partial p}{\partial t} + U \left(\frac{\partial p}{\partial x} \right) = D \frac{\partial^2 p}{\partial x^2}, \quad t > 0,$$

with suitable initial and boundary conditions. In our new model, the apparent convection velocity, $U = U(p, p_x)$ and the apparent diffusivity, $D = D(p)$, are both highly non-linear functions of the pressure. The model incorporate various flow regimes (slip, surface diffusion, transition, continuum) based upon the Knudsen number, Kn , and also includes Forchchiemers turbulence correction terms. In application, the model parameters and associated compressibility factors are fully pressure dependent, giving the model more realism than previous models, see [4]. Given rock properties such as the intrinsic permeability, K , and porosity and tortuosity parameters, the system above is solved for future pressure distributions over a period of time. Details of the model and applications to various reservoir contexts will be presented at the conference.

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NUMERICAL SIMULATION OF THERMAL ENERGY STORAGE WITH PHASE CHANGE MATERIAL AND ALUMINUM FOAM

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Key Words: Latent Heat Thermal Energy Storage System (LHTESS), Phase Change Material (PCM), Metal Foam, Porous medium

A Latent Heat thermal energy storage system (LHTESS) is employed as a thermal buffer, since it avoids the intermittent supply of thermal energy due to the behaviour of the thermal source, in particular the renewable thermal source like the solar radiation. Therefore a LHTESS allows supplying the thermal energy in continuous way. The principal material of a LHTESS is the phase change material (PCM) given that it stores a high quantity of thermal energy during its phase change process thanks to the high value of latent heat. Moreover the thermal energy is stored at quasi-constant temperature because during the phase change process the heat is engaged to change phase and not to raise the temperature [1].

A numerical investigation on Latent Heat Thermal Energy Storage System (LHTESS) based on a phase change material (PCM) is accomplished. The PCM used is a pure paraffin wax with melting over a range of temperature and a high latent heat of fusion. However, its thermal conductivity is very low (about 0.2 W/K m) and a method to enhance the heat transfer is putting the PCM into an aluminum metal foam. The geometry of the system under investigation is a vertical shell and tube LHTESS made with two concentric aluminum tubes. The internal surface of the hollow cylinder is assumed at a constant temperature above the melting temperature of the PCM to simulate the heat transfer from a hot fluid. The other external surfaces are assumed adiabatic or with heat losses toward the external ambient at assigned temperature. A numerical model is employed to simulate the behavior of the PCM embedded with the metal foam. The phase change of the PCM is modelled with the enthalpy porosity theory while the metal foam is considered as a porous media that obeys to the Darcy-Forchheimer law.

The results show that at high porosity the LTE and LTNE models have the same melting time while at low porosity the LTNE has a larger melting time. Moreover, the presence of metal foam improves significantly the heat transfer in the LHTESS giving a very faster phase change process with respect to pure PCM, reducing the melting time more than one order of magnitude. In addition, this numerical model can be further enlarged to simulate different types of metal foam and PCM. The momentum equations are modified by adding of suitable source term which it allows to model the solid phase of PCM and natural convection in the liquid phase of PCM. Local thermal non-equilibrium (LTNE) model is assumed to analyze the metal foam and some comparisons are accomplished with the local thermal equilibrium model assumption. The governing equations are solved employing the Ansys-Fluent 15 code and verification and validation analysis are accomplished. Numerical simulations for PCM, PCM in the porous medium in LTE and in LTNE assumptions are obtained and their results are compared in terms of melting time and temperature fields. Results as a function of time for the charging phase are carried out for different porosities and assigned pore per inch (PPI).

COMBINED EFFECTS OF INTERNAL HEAT GENERATION AND VISCOUS DISSIPATION FOR DOUBLE DIFFUSIVE WITH FORCHHEIMER FLUID MODEL

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Keywords: Double Diffusion, internal heat generation, viscous dissipation

In this paper, a numerical study using shooting technique is applied for a double diffusive flow for the combined effects of internal heat generation and viscous dissipation over a vertical heated plate under the influence of variable fluid properties is carried out. The governing equations of the physical problem are non-linear and coupled partial differential equations for velocity, temperature and concentration distributions. Using a suitable similarity transformation, the governing equations are transformed to ordinary differential equations involving the various non-dimensional parameters of the problem. The fluid characteristics are discussed for variable fluid properties like porosity, permeability, thermal conductivity and solutal diffusivity and the results are compared for particular constant fluid properties. It is observed that our results are well agreed with the earlier works in the literature.

INTERNAL HEAT GENERATION EFFECT ON MIXED CONVECTION HEAT AND MASS TRANSFER OVER A VERTICAL HEATED PLATE WITH SORET AND DUFOUR EFFECTS

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Key Words: Mixed convection, porous medium, boundary layer, internal heat generation, Soret and Dufour parameters

Study and analysis of internal heat generation effect of two-dimensional, steady, laminar, heat and mass transfer mixed convection flow of a viscous incompressible fluid from a vertical heated plate embedded in a sparsely packed porous medium with variable fluid properties such as permeability, porosity, thermal conductivity and solutal diffusivity with the Soret and Dufour effects are considered and studied numerically. The boundary layer flow in the porous medium is governed by Lapwood-Forcheimer-Brinkman extended Darcy model. In this analysis, the governing non-linear coupled partial differential equations are transformed into a system of ordinary differential equations with the help of similarity transformations and solved them numerically by using the shooting technique with Runge-Kutta-Fehlberg scheme and Newton-Raphson method to obtain velocity, temperature and concentration distributions in terms of non-dimensional parameters involved in the physical configuration. The features of fluid flow, heat and mass transfer characteristics are analyzed by in detail to interpret the effects of various significant parameters of the problem. It is observed that the exponential form of internal heat generation enhances melting and impedes freezing. The effect of the Dufour parameter on the local surface temperature becomes more significant and the effect of Soret parameter leads to an increase in the local surface concentration. The effects of the pertinent parameters on the local skin friction coefficient (viscous drag), Nusselt number (rate of heat transfer) and Sherwood number (rate of mass transfer) are also discussed. The obtained results are compared with previously published work of the problem and they are found to be in very good agreement.

PROPOSAL OF UTILIZING UNI-DIRECTIONAL POROUS COPPER FOR EXTREMELY HIGH HEAT FLUX REMOVAL

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Key Words: Uni-directional porous copper, High heat flux, Heat transfer, Evaporation

This paper proposes new heat removal devices utilizing uni-directional porous copper against extremely high heat flux conditions. Before designing those, we discuss some key parameters of porous media to enable a high heat flux removal over 10 MW/m^2 at a low flow rate of water, which are effective thermal conductivity, permeability, liquid supply to a heat transfer surface, and contact thermal resistance between the porous medium and the heat transfer surface. These discussions indicate utilizing the uni-directional porous media as shown in Fig. 1 from the view point of its higher thermal conductivity, direct supply of cooling liquid toward the heat transfer surface, discharge of vapor, reduction in flow resistance and the thermal contact resistance.

The experimental apparatus is composed of the coolant supplying pump, the heat transfer test section, and the heat exchanger. Distilled water is used as cooling liquid. The heat transfer test section mainly consists of the heat transfer block and the uni-directional porous medium attached at the heat transfer surface. High power of eight cartridge heaters are utilized as the heat source and the heat transfer copper block is designed in order to achieve the heat flux of over 10 MW/m^2 at the heat transfer surface of 20 mm in diameter. The uni-directional porous copper has the small holes of 0.5 mm in diameter for the liquid supply and the big holes of 2.8 mm in diameter for the vapor discharge, as shown in Fig. 1 on the right. The thickness is 10 mm and the diameter of the porous medium is 20 mm. As a result, the heat transfer experiments prove that utilizing the uni-directional porous cooling device strongly enhances the evaporation rate of the cooling liquid and drastically improves the heat transfer performance as well as being able to reduce the pressure loss.

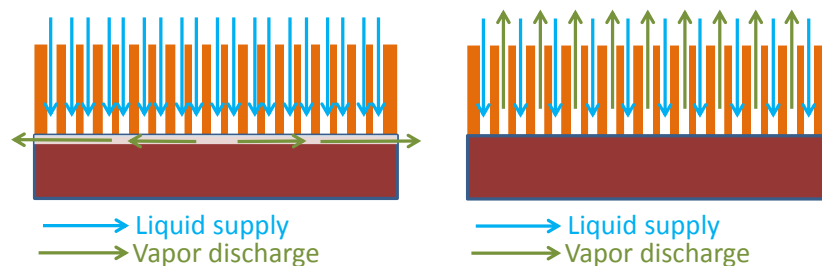


Fig. 1 Utilization of uni-directional porous media for high heat flux removal

GENERATION OF SIMPLE EXTENDED POROUS SURFACE EXPRESSION FROM RESULTS OF PORE-LEVEL CONJUGATE HEAT TRANSFER IN SPHERICAL-VOID-PHASE POROUS BLOCKS

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Key Words: convection, spherical-void-phase, computational fluid dynamics

Studies of convection in porous media continue to be of scientific interest due to the increasing utility of highly-conductive porous materials in heat exchange applications. Of central interest is the ability to model flow and heat transfer through a porous material with high accuracy in a manner that is computationally inexpensive. To this end, use of thermal-equilibrium (TE) or non-thermal-equilibrium (NTE) volume-averaged techniques are of great interest, but use of such methods requires information that is averaged out to be supplied as model coefficients for simple constitutive models that characterize the physical processes. Such models and coefficients are typically derived from either experiments or calculations of pore-level activity in idealized porous materials. It is also of interest to develop simple extended-surface models of porous media that can be used in the development of specialized heat transfer elements. In the present work, a unique geometric model [1] is used to generate spherical-void-phase geometries of several porous microstructures of different porosity and pore diameter. These models are discretized and conjugate results of heat and fluid flow are produced using the commercial software CFX [2]. The results are first used to develop interstitial exchange laws and other coefficients that can be used in similar volume-averaged calculations. The results are then also used to verify a simple one-dimensional model that can be used to characterize the entire porous block as an extended surface. Such a model was originally developed in [3], but without specific verification with pore-level simulations or experiments. The comparison shows that while reasonably accurate approximations can be made of extended porous surfaces, that effects of axial conduction and porous/solid interfaces remain to be sorted out prior to complete utility of the method. Results are presented for two porosities (0.75, 0.85), two pore diameters (400, 800 μ m), four solid-phase conductivities (50, 100, 200, 400 W/mK), and over a range of Reynolds number 10-80, based on the pore diameter. The results demonstrate the viability of the simple approach for conducting heat transfer calculations. The topic under consideration fits nicely into the "Natural and Forced Convection in Porous Media" and "Advanced Mathematical Approaches to the Modelling of Porous Media" themes of the conference.

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EFFECTS ON THE PORE STRUCTURE AND PERMEABILITY CHANGE BY COKE DEPOSITION DURING CRUDE OIL IN-SITU COMBUSTION

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Key Words: In-situ combustion; coke deposition; permeability; X-ray micro-tomography; Lattice-Boltzmann simulation

In-situ combustion (ISC) is an enhanced oil recovery technique to exploit the unconventional crude oil resources with high recovery efficiency. Great amount of reaction heat is released in-place by burning the solid residue, so-called coke at the combustion front with the temperature higher than 400°C. Significant open ISC questions include the effect of coke formation on the pore structure and permeability. Coke deposition reduces the permeability and increases the permeability heterogeneities which will affect the oxygen transport in the formation, thereby influencing the oxygen participating reactions downstream. However, the existing empirical or semi-empirical relationships are still questionable to model the permeability change due to coke deposition. In the study, a high temperature and high pressure experimental apparatus was constructed to physically simulate the coke formation during the ISC processes. A series of coked grain clusters with different amount of coke deposition were produced by controlling the reaction conditions. The coke concentration in each coked grain cluster was measured by Thermogravimetric analysis. The coke distribution in coked grain cluster was viewed by a scanning electron microscopy (SEM). The porosity of coked sand samples with approximate coke concentrations was acquired by mercury porosimeters. High resolution X-ray micro-tomography (μ CT) was combined with Lattice-Boltzmann computer simulation (LBM) to investigate the changes in the pore structure and permeability of the coked porous medium. The 1 μ m resolution of 3D digital cores allowed accurate characterization of the coked grain cluster microstructure with the material distinguishment including the coke, glass beads and air by proper image processing. The image processing mainly included contrast enhancement, noise filters, morphological modifications, then followed by watershed segmentation. The digital core structural properties with different coke deposition were extracted by image analysis, such as porosity, tortuosity and pore throat diameter. The porosity evolution with coke deposition obtained by image analysis coincided with the experimentally measured. The results showed the capability to track the pore structure change with coke deposition by the μ CT and the image processing. Due to the klinkenberg effect existence in the coked porous medium indicated by the previous experiments, the gas slippage was considered in gas phase LBM for bulk permeability prediction. The klinkenberg effect was estimated and the Klinkenberg-corrected permeability was determined for the digital core with different coke deposition. The permeability damage compared against none coke deposition was close to the prediction by Kozeny-Carman relationship, while the difference increased rapidly with more coke deposition. The increasing complication of the pore structure with coke deposition resulted in the non-linear evolution of permeability damage. Finally, a correlation of the permeability with the pore structure macroscopic properties was developed at the Darcy scale, which is applicable to ISC processes in sandstone reservoirs.

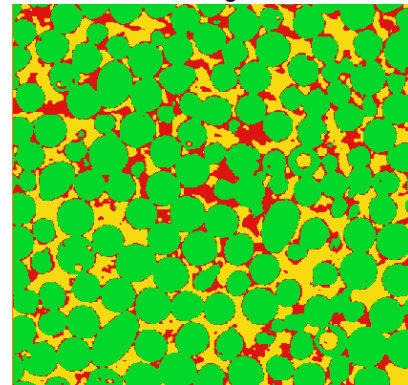


Figure 1: Slice of digital core including coke (red), glass beads (green) and air (yellow)

EFFECT OF THE VARIABLE POROSITY ON THE HEAT TRANSFER PROCESS IN SOLAR AIR RECEIVER

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Key Words: Porous media, variable porosity, heat transfer, air receiver

Solar air receiver is the core component of central receiver system (CRS) in solar thermal power plants due to the unique feature of some porous medium like silicon carbide foam ceramic and so on. In the air receiver, the porous material receives the concentrated sunlight from the heliostat field and heats up the pumped inlet air by convection and radiation. The incident radiation is distributed in the inner space of the porous medium rather than located on the boundary of the heated face in the front of the receiver. Aiming at this phenomenon which called volumetric effect, we propose a novel solar air receiver using the porous medium with variable porosity along the incident direction to optimize its heat transfer process and increase the thermal efficiency of the receiver. For this kind of porous medium, the effect of the variability of the porosity ϵ on the temperature and radiative heat flux distributions and also the thermal efficiency of the air receiver will be analyzed systematically. Our analysis demonstrated that the structure with variable porosity will enhance the transfer of radiative energy into the porous medium, consequently decreases the thermal radiative loss at the inlet and increases the thermal efficiency of the air receiver.

EFFECTIVE TRANSPORT PROPERTIES OF DRUG DELIVERY SYSTEMS: POROUS GRANULES AND TABLETS

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Key Words: diffusion, magnetic resonance imaging, uv imaging, dissolution, pharmaceutical formulation

Solid dosage forms such as tablets, granules or capsules represent over 80% of all pharmaceutical products. Modern pharmaceutical formulations are designed so as to release the active pharmaceutical ingredient (API) at a well-defined and reproducible rate. Two main classes of dosage forms can be distinguished: rapid release formulations (which are designed to disintegrate rapidly and dissolve the API within the shortest possible time), and sustained release formulations (which are designed to release the API gradually over a prolonged period of time, typically 24 hours). In both cases, the effective transport properties of the drug carrier (granule, tablet) play a crucial role. The wetting and imbibition of gastric juices into the porous structure of the tablet determines the time-scale over which the individual drug particles will be contacted with the dissolution medium, which the diffusion of the dissolve drug substance through the tablet structure determines the release rate. Pharmaceutical formulations typically contain not only the API particles but also several auxiliary components (excipients) such as fillers, disintegrants, binders, controlled release polymers, lubricants, surfactants, etc. The porous structure is formed hierarchically, starting with the blending of the initial powders with given particle size distributions, followed by dry or wet agglomeration into granules, which are then compressed into the final tablets. The understanding of a relationship between the material properties of the formulation, the parameters of the manufacturing process, and the effective transport properties (water permeability and drug diffusivity) of the final pharmaceutical product is therefore crucial when developing new solid dosage forms.

In this contribution, we will present our recent progress on the combination of 3D imaging methods (MRI, micro CT), spectroscopic analytical methods (UV/Vis spectrophotometry) and mathematical modeling to evaluate the effective transport properties of pharmaceutical granules and tablets. By systematically changing the manufacturing process parameters (granulation conditions, tableting pressure) and the formulation composition (ratio of API and excipients), we have prepared a series of structures with systematically varying drug release profiles. The rate-limiting step was identified in each case, and three limiting regimes were found: drug release limited by water transport into the tablet, drug release limited by intrinsic dissolution kinetics of the API, and drug release limited by the diffusion of API from the tablet. The knowledge of these limiting regimes then and their dependence on the formulation and processing parameters then allows rational choices to be made when designing new drug products.

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MODELING FLOW, HEAT AND MASS TRANSFER IN A POROUS BIOMASS PLUG – WHEN USED IN AN ELECTRICALLY HEATED TOBACCO SYSTEM

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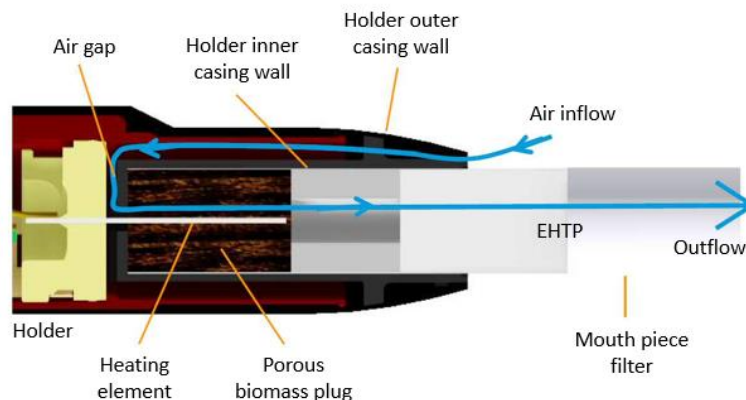
Key Words: Heat and mass transfer, biomass, Electrically Heated Tobacco System

Heating porous biomass samples is utilized in many industries for drying or extracting Volatile Organic Compounds (VOC) from the biomass. The heating may trigger physical and chemical processes within the material, such as release of VOC, thermal degradation and evaporation. Most of the processes triggered by the increased temperature are occurring simultaneously and are strongly interdependent. For most practical applications, it is important to have control of the complex processes occurring during heating to generate stable and controllable release of VOC. This is the case for products delivering the released VOC to consumers by inhalation, as is the case of an Electrically Heated Tobacco System (EHTS). Modeling the physical and chemical processes numerically using Computational Fluid Dynamics (CFD) provides valuable information on the product functioning upon heating and on the flow, heat and mass transfer taking place in the porous biomass sample. CFD can in combination with experimental data of the temperature and released VOC also be used to validate or identify gaps in the understanding of the product functioning, which further can be used to demonstrate the operating conditions that the biomass is exposed to during product use.

In this work we present our approach to model transient and density varying flow, heat and mass transfer of an anisotropic porous biomass plug when used in an EHTS. The two main components of the EHTS considered (also referred to as the Tobacco Heating System (THS)) in this work are the Electrically Heated Tobacco Product (EHTP) containing the biomass plug and the Holder into which the EHTP is inserted and which heats the porous biomass by means of an electronically controlled heater, as shown in Figure . The heating triggers release of VOC from the biomass, locally increasing the density of the gas in the surrounding pore space. Air at ambient temperature is periodically drawn through the heated EHTP following a puffing protocol, transporting the released VOC through the EHTP. This results in both thermal and chemical nonequilibrium conditions with interstitial energy and mass transfer occurring between the gas and solid phases. Moreover, when cooled down, the VOC can reach supersaturation, resulting in aerosol droplet formation. To account for all these phenomena, volume averaged transient and density varying mass, momentum and energy conservation equations for multicomponent aerosols in anisotropic porous media under thermal and chemical nonequilibrium are solved using a segregated collocated variable finite volume algorithm implemented into the OpenFOAM® open source CFD software based on C++ [1], [2].

The simulated temperature in the porous biomass plug is compared to experimental data obtained by thermocouples inserted into in an EHTP. In addition, the simulated amount of VOC exiting the EHTP is compared to experimentally measured data. The close match between numerical and experimental results

indicate that most relevant physical and chemical processes are understood and accounted for in the numerical model.



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Figure 1 – Flow path through the Holder and the EHTP containing a porous biomass plug of the considered EHTS.

AN INNOVATIVE CULTURE TECHNIQUE FOR MICROALGAE USING HOLLOW FIBER MEMBRANES

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Keywords: Microalgal culture, Membrane transport, Hollow fiber membrane, Microalgae growth rate

A hollow fiber culture system has been proposed for supplying the carbon dioxide to the microalgae, to replace the conventional air bubbling system which has been adopted to supply carbon dioxide in most conventional microalgal culture. In order to examine the usefulness of hollow fiber membranes for the microalgal culture, the microalgal growth rate for *Chlorella sp.* and the effective mass transfer coefficient of carbon dioxide through the hollow fiber membranes have been measured using the proposed photobioreactor filled with hollow fibers. The microalgal growth rate using hollow fiber membranes was found to be three times greater than that observed in the conventional non-membrane photobioreactor. An experimental investigation has been conducted so as to evaluate the effect of the volume flow rate of the carbon dioxide and its concentration of the feed air through the hollow fibers on the microalgal growth rate. The present study clearly indicates that the hollow fiber membrane is quite useful for the microalgal culture in terms of enhancing both microalgal growth rate.

EFFECT OF NEWTONIAN HEATING ON BIOCONVECTION OF NANOFLUID OVER STRETCHING SHEET WITH GYROTACTIC MICROORGANISMS

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Transport processes in nanofluids and their importance in biomedical applications and process industries has gained considerable attention in recent decades [1, 2]. Bioconvection in a horizontal layer with heat and mass transfer of nanofluid containing gyrotactic microorganisms along a stretching sheet taking into account the Newtonian heating boundary condition is investigated numerically. In the modelling of nanofluid, both Brownian motion and thermophoresis effects are incorporated into the nonlinear differential equations. The governing equations are reduced to a system of couple non-linear ordinary differential equations for momentum, energy, nanoparticle concentration and dimensionless motile microorganism density, with using appropriate similarity transformations and then tackled numerically using the fifth order Rung-Kutta-Fehlberg scheme with shooting technique. Results are presented in graphical forms for dimensionless velocity, temperature, nanoparticle volume fraction and motile microorganisms in the presence of magnetic field. The solution depends on a Prandtl number, Newtonian heating parameter, Brownian motion number, Lewis number, buoyancy ratio parameter, thermophoresis number and bioconvection Lewis number. The results show dimensionless velocity and temperature distributions on the stretching sheet increase with the increase of Newtonian heating parameter, whereas nanoparticle volume fraction and motile microorganism density profile decrease with increasing it.

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DIRECT NUMERICAL SIMULATION OF REACTIVE FLOW THROUGH A FIXED BED OF CATALYST PARTICLES

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Key Words: Packed bed, heat transfer, mass transfer, reactive flows.

Many catalytic refining and petrochemical processes involve two-phase reactive systems in which the continuous phase is a fluid and the porous phase consists of rigid particles randomly stacked. Improving both the design and the operating conditions of these processes represents a major scientific and industrial challenge in a context of sustainable development. Thus, it is above all important to better understand all the intricate couplings at stake in these flows: hydrodynamic, chemical and thermal contributions. The objective of our work is to build up a multi-scale modelling approach of reactive particulate flows and at first to focus on the development of a microscopic-scale including heat and mass transfers and chemical reactions for the prediction of reactive flows through a dense or dilute fixed bed of catalyst particles. A first step is the upgrading and the validation of our numerical tools via analytical solutions or empirical correlations when it is feasible. Then we illustrate the assets of our simulation method on a reactive flow through a pack of different shapes of particles. Our method is implemented in our massively parallel numerical platform PeliGRIFF (www.peligriff.com) that already enable us to improve the accuracy of predictions in scales which interest engineers in process engineering. In fine, this processus will enable to take a step towards the enhanced design of semi-industrial processes.

NUMERICAL INVESTIGATION OF THE PHASE CHANGE IN TRANSPIRATION COOLING WITH THE VOF METHOD

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Key Words: phase change, transpiration cooling, numerical simulation, VOF model

Transpiration cooling with phase change is numerically investigated in the present work. As shown in Figure 1, a liquid coolant flow is injected into a porous medium from the bottom side. The porous medium receives heat from the hot gas on the top surface and heats the coolant. Thus, phase change can occur in this porous medium. The surface temperature, the heat flux received by the porous medium, the phase distribution and the flow and cooling characteristics are the most important unknowns on this topic.

A two-dimensional model coupling the heat transfer and flows in porous media and the hot gas zones is developed to simulate the above phenomenon. With the assumptions of local thermal equilibrium and the clear interface between the liquid and gas phases, the volume-of-fluid (VOF) method can be used in this model. This clear interface is tracked by the VOF method and divides the computed zone into the liquid phase region and the gas phase region. On this liquid-gas interface, a phase change model should be applied in this modeling. Thus, the modified Lee's phase change model is proposed and used to insure the phase change flow in porous media can be converged.

The porous medium surface temperature distributions were compared between the numerical results and our experimental data and they had good agreements.

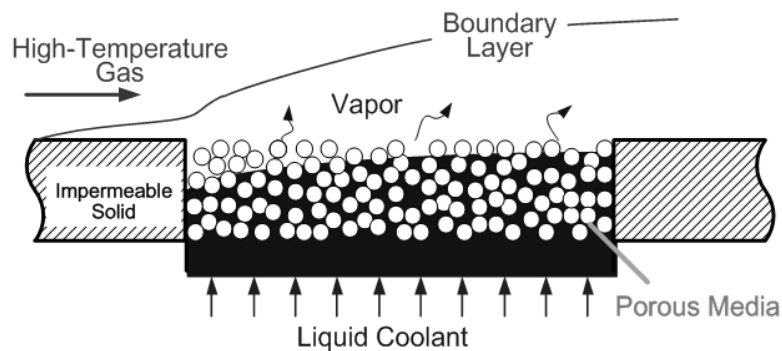


Figure 1 – Schematic diagram for transpiration cooling with phase change

A MINI-REVIEW ON THE FRACTAL-MONTE CARLO METHOD AND ITS APPLICATIONS IN POROUS MEDIA

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Key Words: Fractal, Monte Carlo Method, Porous Media

Porous media widely exist in nature such as soil, rocks, sandstones, oil/gas/water reservoirs, biological tissue and organics, etc., and in many sciences and engineering applications. Since microstructures of porous media are extremely complicated, this makes very difficult to predict the transport properties such as thermal conductivities and permeabilities of porous media by analytical solutions. Usually, numerical simulations such as control volume method, molecular dynamics and Lattice Boltzmann method etc. are often applied. However, results by numerical simulations are often correlated as empiric expressions, which usually contain one or more empiric constants. Fortunately, many researchers found that the microstructures of porous media have the fractal characters, and transport properties such as thermal conductivities, permeabilities, and gas diffusion coefficients in porous media could be found by applying the fractal geometry theory and technique. In this mini-review, the fractal geometry theory combined with the Monte Carlo method are summarized, and then the current research progresses in several areas are reviewed, including in the areas of permeabilities of porous media, thermal conductivities of porous media, thermal conductivities of nanofluids, rough surfaces, gas diffusivities in porous media and boiling heat transfer etc. Finally, some comments are made regarding the future possible applications.