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Review Article

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Review: heat and mass transfer in porous medium, mathematic/numerical models and research directions

Abstract

This paper is a mini-review for research studies (range from year 2000 to 2018) on porous medium in China. It includes basic mathematic and numerical models for heat and mass transfer through porous medium. And then, several advanced contemporary research topics on porous medium in China are outlined.

Keywords: porous medium, heat/mass transfer in porous medium, adsorption, filtration, combustion.

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Introduction

As key functional material, porous medium was used in a wide range of applications due to its good thermal performance and semi-permeable properties. These applications involve aerospace,[1] semi-conductors[2–4], bio-sensors,[5–8] environmental energy saving,[9–13] medicine,[14,15] infrastructure construction,[16–18] fuel cell,[19,20] petrochemicals[21,22] and so on. Thermal research studies in the above areas were generally concerned on separation/purification process, heat preservation, chemical catalysis, medical engineering, etc.

Basic mathematic models for porous medium

In the analysis of mass transfer process for porous medium, the mathematic models normally used could be traced back to Darcy's law (1856).[23] The law was formulated by Henry Darcy based on the results of experiments on the flow of water through beds of sand. Its application to form numerical calculation in porous medium is even populous in today's research. After decades of development, Darcy's law was gradually improved, for example, Forchheimer's amendment[24] on inertia force, Brinkman's amendment[25] on viscous force, and Knudsen diffusion or Klinkenberg effect,[26] etc. Those were mathematic descriptions on flow inside porous medium. Another sort of models directly describes trans-porous medium (or usually called trans-membrane) flow accompanied with membrane solute filtration. More comprehensive mathematic presentation for the filtration process was accomplished by Kedem-Katchalsky (K-K)'s equations.[27,28] (Table 1) listed all these mathematic models for porous medium.

Table 1 Mathematic models used in porous medium

Darcy's law	$q = -\frac{k}{\mu}\nabla p$	Where q is the flux, k is the cross sectional area, u is viscosity, and ∇p is the pressure gradient.
Darcy-Forchheimer law	$\frac{\partial p}{\partial x} = -\frac{\mu}{k}q - \frac{\rho}{k_1}q^2$	Where the additional term k_1 is known as inertial permeability.
Brinkman form of Darcy's law	$-\hat{a}\nabla^2 q + q = -\frac{k}{\mu}\nabla p$	Where β is an effective viscosity term.
Darcy's law for gases in fine medium	$q = -\frac{k^{eff}}{\mu}\nabla p$, $k^{eff} = k\left(1+\frac{b}{p}\right)$	Where b is known as the Klinkenberg parameter.
K-K equations for trans-membrane flow	$J_v = L_p\Delta p - \sigma L_p RT\Delta C$ $J_s = (1-\sigma)C_m J_v + P_s\Delta C$	Where L_p is hydraulic permeability, Δ_p is trans-membrane pressure, ΔC is solute concentration difference, C_m is average solute concentration inside the porous membrane, J_s is ultra-filtration velocity, J_s is solute flux, σ is solute reflection coefficient, as well P_s is diffusive coefficient.

Contemporary numerical studies for porous medium always inside a complicated system. In most research works, the porous material was majorly considered as uniform. Under such assumption, Navier-Stokes equations were introduced to describe the flow and thermal properties inside a porous medium. In a relatively comprehensive system, by combining Darcy-Forchheimer law, Jiang and Lu's work[29] displayed how to use turbulence $\kappa-\omega$ model to describe the flow and heat transfer inside sintered porous plate channels. In China, their work is representative for the followers and became a mile-stone for the studies inside porous medium.

Our research work on porous plate channels started from hemodialysis process.[30] It tells a story of both ultra filtration on sideway channel wall and solute distribution inside channels. Multiple-scale calculations were applied in such a system: the flow inside the straight channel was calculated by Simple R algorithm, meanwhile, the ultra filtration flow profile was determined by K-K equations.

Since this paper is a required two page mini-review, in the following, I will tip out most recent advanced research topics of porous medium only in the following two areas:

i. Adsorption /filtration

ii. Combustion with porous medium

Advanced studies

Adsorption/filtration

Surface adsorption occurs in many gas/fluid separation processes (such as nitrogen/oxygen separation, pressure-swing absorption process). The research in this field covers from single gas adsorption isotherms (Langmuir, BET, DR isotherms, etc.), real gas equations of state (mBWR, R-K, Viral, Van der Waals models, etc.), to predicting the equilibria of mixed-gas adsorption (Myers' IAST ~RAST MIAST models.[30–32]

Filtration process typically uses semi-permeable membrane or porous column; and these processes are divided into four categories:

i. Micro-filtration (filtrated particle size ranges from 1 micron to several hundred microns).

ii. Ultra-filtration (submicron filtration process);

iii. Nano-filtration (particle size usually located in several nano-meters).

iv. Reverse osmosis (only water molecules can be filtrated).

K-K equations becomes dominant mathematic model to analyze filtration process.[33,34] Also, MD,[35] SPH[36] methods were adopted to calculate the phantoms inside nano/micro pores.

Most recent studies in Chinese government projects also include multiple phases during separation process (such as liquid nitrogen separation, helium separation in cryogenic temperature; and oil or sea water distillation using porous column). In this studies,[37-45] CSF/VOF models were adopted to trace phase surface change and SPH or CFD methods were used to calculate pure single phase flows.

A research inclination arriving recently in our lab is magnetic adsorption. In this initiative research field, adsorbents are magnified and controlled by gradient magnetic field.[46,47] To study the pure physical phenomenon of this peculiar adsorption process, DEM/DPM model is assumed to be adopted. Since the motion of the particles are controllable and go against the carrying solution, turbulence LES model is also concerned because of accumulation of some magnetic particles. Even the numerical study has not yet been put into run-way, the study is valuable not only because it could be industrially applied, but because it is much more significant in that it is an initiative pure physics problem (controllable opposite direction two-phase flows inside a porous adsorption system) that ancestors never touched.

Combustion with porous medium

Typically, most combustion research studies were related to gas engines (such as aerospace engine and vehicle engine). These studies usually use LES turbulence model to analyze the power efficiency produced by combustion. Meanwhile, chemical reactions are always introduced to CFD simulations by equations of reaction rates. Also, porous film cooling was studied inside aerospace engines.[1,48–50] These studies were majorly focused on gaseous porous film cooling.[51–55]

Combustion inside porous medium is an innovative topic in combustion research. This new technology is superior to conventional combustion in that:

i. Due to the huge amount of tiny reaction spaces, the combustion is evenly fractionized, such that its thermal efficiency is very high.

ii. its combustion discharge is very little

iii. It does not require large combustion facilities. The key issue inside porous medium combustion is premixed combustion.[56–58]

As typical example of combustion inside porous medium, sintering process played an important role in most of Chinese steel industry. And today, accompanied with high-speed economic development in China, it becomes a big pollution contributor due to its high energy consumption and low residual heat recovery. Flue gas recirculation sintering (FGRS) technology can reduce flue gas emissions and reuse waste heat effectively in iron ore sintering. Five FGRS systems have been built or transformed in China since 2013.[59] Chinese combustion researchers also get their directions from this point. Iron ore sintering process is a combustion process inside porous medium; it covers chemical reactions, heat radiation, convection, as well as conduction thermal processes. Due to the high-energy gases consumed and produced inside the pores, the research in this field becomes very complicated.

Conclusion & future aspects

This paper reviewed recent (after year 2000) research studies as well as projects deployed in the area of porous medium in China. The majorly used mathematic models as well as numerical calculation methods for porous medium were also browsed in this paper. Accompanied with parallel computing hardware development (such as GPU computing and quantum computing hardware), in my personal opinion, I would suggest that the future research studies should be more focused on heat & mass transfer details to disclose more and more real story inside porous medium:

Dynamic porous medium combustion

i. Since the porous material could also participate in the process of combustion,[59] its size shrinks while the hole' space increases. The research studies herein are really interesting because the reaction products sometimes are not gases but solids which will cause the reaction speed slow-down. Moreover, the gases that generated inside porous medium could also stall the chemical reaction in a way that suffocates the reaction. So, how to promote the combustion efficiency becomes the key point of these studies.

ii. The heat transfer inside the porous medium during combustion is also complicated. There includes conduction, convection as well as radiation thermal processes. However, the boundary conditions could not be assumed as constant or insulated since the combustion is dynamic according to vigorous chemical reactions inside different porous areas; such that even the combustion flows are premixed, the combustion in entrance area could be far different from that in outlet area.

Dynamic porous medium adsorption/filtration

i. As an example for adsorption, our lab already started research on magnetic adsorption as mentioned in this paper. It is a far more interesting pure physics study that it works on a moving "magnetic porous medium (composed by dispersed particles)" inside a flow field. Since the particles are sometimes accumulated in different size according to magnetic force, the flow field is turbulent. Under this condition, the adsorption process is also dynamic. The adsorption potential on solid surface is obviously influenced by turbulent vicious force. Needless to say, this study will also exploit the studies of multiphase turbulence flow.

ii. For filtration process, the studies of molecules passing through porous medium will be more realistic. For example, as fundamental construction molecules of protein, the exchange of amino-acids through cell membranes or polymer membrane will be highly concerned in the study of hemodialysis process.[60]

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Conflict of interest

The author declares that there is no conflict of interest.

References

1. Cao YZ, Tao Z, Xu GQ. Heat transfer inside aerospace engine. *Beihang's aerospace press*. China, 2005.
2. Martin CR. Nanomaterials: a membrane-based synthetic approach. *Science*. 1994;266(5193):1961–1966.
3. Xu DS, Chen DP, Xu YJ. Preparation of II-VI group semiconductor nanowire arrays by dc electrochemical deposition in porous aluminum oxide templates. *Pure and Applied Chemistry*. 2000;72(1-2):127–135.
4. Zhao JM, Gu F, Zhao XH, et al. Semiconductor properties of anodic oxide film formed on aluminum. *Acta Physico-Chimica Sinica*. 2008;24(01):147–151.
5. Kohli P, Wirtz M, Martin C. Nanotube membrane based biosensors. *Electroanalysis*. 2010;16(1–2):9–18.
6. Pérez S, Sánchez S, Fàbregas E. Enzymatic strategies to construct L-Lactate biosensors based on polysulfone/carbon nanotubes membranes. *Electroanalysis*. 2012;24(4):967–974.
7. Wang X, Yang T, Feng Y, et al. A Novel hydrogen peroxide biosensor based on the synergistic effect of gold-platinum alloy nanoparticles/polyaniline nanotube/chitosan nanocomposite membrane. *Electroanalysis*. 2010;21(7):819–825.
8. Manesh KM, Kim HT, Santhosh P, et al. A novel glucose biosensor based on immobilization of glucose oxidase into multiwall carbon nanotubes-polyelectrolyte-loaded electrospun nanofibrous membrane. *Biosensors & Bioelectronics*. 2008;23(6):771–779.
9. Malico I, Mujeebuc MA. Potential of porous media combustion technology for household applications (review article). *International Journal of Advanced Thermofluid Research*. 2015;1(1).
10. Mishra NK, Muthukumar P, Panigrahy S. A review on clean combustion within porous media, chapter in book. *Air Pollution and Control*. 2018;209–224.
11. Howell JR, Hall MJ, Ellzey JL. Combustion of hydrocarbon fuels within porous inert media. *Progress in Energy and Combustion Science*. 1996;22(2):121–145.
12. Mujeebu MA, Abdullah MZ, Bakar MZA, et al. A review of investigations on liquid fuel combustion in porous inert media. *Progress in Energy & Combustion Science*. 2009;35(2):216–230.
13. Hideki K, Hisao M, Minoru M. Energy-saving drying technology for porous media using liquefied DME gas. *Adsorption*. 2008;14:(4–5)467–473.
14. Solano Umaña V, Vega-Baudrit. Micro, meso and macro porous materials on medicine. *Journal of Biomaterials and Nanobiotechnology*. 2015;6:247–256.
15. Vafai K. Porous Media: Applications in Biological Systems and Biotechnology. Florida, United States: CRC Press; 2010.
16. Sun JY, Huang K, Jiang HQ. Research on physical properties and durability of pervious cement concrete. *Journal of Building Materials*. 2007.
17. Huang B, Wu H, Shu X, et al. Laboratory evaluation of permeability and strength of polymer-modified pervious concrete. *Construction and Building Materials*. 2010;24(5):818–823.
18. Cui Y, Gary P, Lisle TE, et al. Experimental study on properties of pervious concrete pavement materials. *Cement & Concrete Research*. 2003;33(3):381–386.
19. Sadeghi E, Bahrami M, Djilali N. Analytic determination of the effective thermal conductivity of PEM fuel cell gas diffusion layers. *Journal of Power Sources*. 2008;179(1):200–208.
20. Karimi G, Li X, Teertstra P. Measurement of through-plane effective thermal conductivity and contact resistance in PEM fuel cell diffusion media. *Electrochimica Acta*. 2010;55(5):1619–1625.
21. Broseta D, Medjahed F, Lecourtier J, et al. Polymer adsorption/retention in porous media: effects of core wettability on residual oil. *Spe Advanced Technology*. 1995;3(1):103–112.
22. Zhang G, Seright RS. Effect of concentration on HPAM retention in porous media. *Spe Journal*. 2014;19(3):373–380.
23. Ingham DB, Pop I. Transport phenomena in porous medium. Oxford, Pergamon press /Elsevier science, 1998.
24. Forchheimer PH, Wasserbewegung durch doden. Radiation Absorption and Variable Electrical Conductivity Effect on High Speed MHD Free Convective Flow past an Exponential Accelerated Inclined Plate. *Zeitz Ver Duetch Ing*. 1901;45:1782–1788.
25. Brinkman HC. A calculation of the viscous force exerted by a flowing fluid on a dense swarm of particles. *Applied Science Research*. 1949;1:27–34.
26. Klinkenberg LJ. The permeability of porous medium to liquids and gases, in: *API-41-200. American Petroleum Institute, New York, API-41-209*, 1941.
27. Kedem O, Katchalsky A. Thermodynamic analysis of the permeability of biological membranes to non-electrolytes. *Biochem. Biophys. Acta*.1958;27:229–246.
28. Kedem O, Katchalsky A. A physical interpretation of the phenomenological coefficients. *J Gen Physiol*. 1961;45:143–179.
29. Jiang PX, Lu XC. Numerical simulation of fluid flow and convection heat transfer in sintered porous plate channels. *International Journal of Heat and Mass Transfer*. 2006;49(9–10):1685–1695.
30. Myers AL, Prausnitz JM. Thermodynamics of mixed-gas adsorption. *Aiche Journal*. 1965;11(1):121–127.

31. Wigton A, Kilduff JE. Modeling trichloroethylene adsorption by activated carbon preloaded with natural dissolved organic matter using a modified IAST approach. *Environ Sci Technol*. 2004;38(22):5825–58233.

32. Li M, Zhou L, Wu Q. Progress in predicting the equilibria of multi-component gas/solid adsorption. *Progress in Chemistry*. 2002;14(2):93–97.

33. Lu JF, Lu WQ. A numerical simulation for mass transfer through the porous membrane of parallel straight channels. *International Journal of Heat and Mass Transfer*. 2010;53(11–12):2404–2413.

34. Lu JF, Chu Y, Lu WQ. An investigation for the usability of K-K equations for nano porous membranes. ASME 2009 Second International Conference on Micro/Nanoscale Heat and Mass Transfer, Shanghai, China, 2009. pp.513–518.

35. Chu Y, Lu JF, Lu WQ. Molecular dynamics simulation of fluid transport in nanoscale pore of porous medium, 6th International Symposium on Multiphase Flow, Heat Mass Transfer and Energy Conversion, 2009, Xian, China.

36. Chu Y, Lu JF, Lu WQ. Numerical simulation of fluid transport in a single micro-nano pore of porous membrane. *ASME 2009 Summer Heat Transfer Conference*. 2009, Shanghai, China.

37. Ren B, Ye XW, Gao R. SPH modelling of wave interaction with porous structures. *The Ocean Engineering (a Chinese Journal)*. 2012;30(2):46–52.

38. Qiang HF, Chen FZ, Gao WR. Smoothed particle hydrodynamics method with modified surface tension and its implementation. *Chinese Journal of Computational Physics*. 2011;28(3):375–384.

39. Liu D, Guo YC, Lin WY. Deformation of drop and surface tension modeling using SPH. *Physics of gases-theory and applications*. 2012;7(2):29–34.

40. Dong LF, Zhang H, Chen JX. Surface tension simulation for SPH fluid based on IIF model. *Journal of Graphics*. 2016;37(3):302–307.

41. Cheng ZF, Wang XL, Liv P. Numerical simulation of free seepage field in RCC dams based on VOF method. *Journal of Hydraulic Engineering*. 2015;46(5).

42. Wang J, Chen W, Mao YB. Characteristics of the porous medium enhanced pool boiling heat transfer. *Refrigeration Cryo. & Supercond*. 2015;43(3).

43. Zhang J, Fang J, Fan BQ. Advances in research of VOF method. *Advances in Science and Technology of Water Resources*. 2005;25(2).

44. Dong Z, Zhan JM. Comparison of existing methods for wave generating and absorbing in VOF-based numerical tank. *Journal of Hydrodynamics*. 2009;24(1):15–21.

45. Tong L, Yu G, Peng Z. Coupled simulation of two-phase flow based on VOF model and dynamic mesh technology. *Journal of Wuhan University of Technology (Information & Management Engineering)*. 2008;30(4):525–528.

46. Lu JF, Lu WQ. Derivation for electric current regulation equation of a gradient magnetic field to control suspending magnetic particles inside dialysate solution. *Journal of Heat Transfer*. 2017;140(1):012801.

47. Lu JF, Zhang H, Lu WQ. A computational design of a magnetic field applied to control magnetic adsorbent used in liquid/gas adsorption processes. *International Communications in Heat and Mass Transfer*. 2014;53:18–25.

48. Arai M, Suidzu T. Porous ceramic coating for transpiration cooling of gas turbine blade. *Journal of Thermal Spray Technology*. 2013;22(5):690–698.

49. Smith AB, Kempster A, Smith J. Vapor aluminide coating of internal cooling channels, in turbine blades and vanes. *Surface & Coatings Technology*. 1999;120–121(1):112–117.

50. Ario S, Vesna M. Protection against oxidation of internal cooling passageways in turbine blades and vanes. *Journal of the Japan Society of Mechanical Engineers*. 1998;64(5):894–898.

51. Ni M, Zhu HR, Qiu Y, et al. Review of aero-turbine blade cooling technologies. *Gas Turbine Technology (Chinese Journal)*. 2005;18(4):25–38.

52. Cao S, Mo R, Gong ZW. Research on parametric modeling of aeronautic turbine blade film hole. *Aeronautical Computing Technique (Chinese Journal)*. 2011;41(3):77–81.

53. Kong MZ, Zhu HR, Liu SL, et al. Internal heat transfer characteristics of lamilloy configurations. *Chinese Journal of Aeronautics*. 2008;21(1):28–34.

54. Liang WY, Zhou LS. Heat transfer experimental investigation on full film cooling. *Gas Turbine Experiment and Research*. 2009;22(3):40–44.

55. Jiang LP, Xu KJ, Sui YS. Application and development of cooling technology on turbine blades. *Journal of Naval Aeronautical Engineering Institute (Chinese Journal)*. 2002;17(1):129–132.

56. Shi JR, Combustion mechanism and flame characteristics of the super adiabatic combustion of premixed gases in porous media. 2007.

57. Wang SJ, Sun R. Numerical investigation of premixed combustion in porous media. *Energy Conservation Technology (Chinese Journal)*. 2007;25(144).

58. Wu XC, Cheng LM, Wang EY. Investigation on premixed combustion in porous medium burner. *Power System Engineering (Chinese Journal)*. 2003;19(1):37–40.

59. Wang G, Wen Z, Lou GF, et al. Mathematical modeling of and parametric studies on flue gas recirculation iron ore sintering. *Applied Thermal Engineering*. 2016;102:648–660.

60. Lu JF, Zhang H, Fan W. An investigation of a novel parallel computation scheme designed for a simulation of amino-acid leaking problem inside α-Al2O3 nano-channels. *Applied Mechanics and Materials*. 2013;275-277:607–611.