Brief overview on Local Thermal Non-Equilibrium modeling of heat and mass transfer in open porous materials

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RÉSUMÉ. *Le processus de transfert de chaleur dans les milieux poreux a été largement étudié numériquement en raison de nombreuses applications importantes telles que la géothermie, les réacteurs chimiques, l'hydrogéologie, les caloducs, les échangeurs thermiques à matrice solide et l'isolation thermique des bâtiments. Dans la théorie classique des milieux poreux, on suppose un équilibre thermique local entre la phase fluide et la phase solide, les températures du fluide et du solide atteignant rapidement une valeur de température d'équilibre. Cependant, l'équilibre thermique local dans les milieux poreux pose un problème, car la vitesse de transfert de chaleur entre le fluide et le solide risque de ne pas être assez rapide pour atteindre un équilibre thermique local (LTE) en raison de leurs propriétés de diffusion thermique. Par conséquent, cet article présentera l'importance de l'utilisation de la modélisation LTNE pour le transfert de chaleur et d'humidité dans les milieux poreux. La présente revue de la littérature montre que la modélisation LTNE apporte plus de richesse et finesse dans l'analyses des transferts thermiques dans les milieux poreux. Nous concluons que cette dernière est plus précise que le LTE pour étudier la convection thermique à l'interface à travers un milieu poreux. Malgré cela, nous avons constaté qu'il subsiste encore un manque de développement sur le non-equilibre hygrothermique, en particulier avec les matériaux isolants biosourcé. Dans ce cas, il est important d'analyser l'augmentation substantielle de la capacité de dissipation de la chaleur à l'intérieur des matériaux, en particulier pour les matériaux à haut rapport de conductivité thermique solid-fluide.*

ABSTRACT. *The process of flow and heat transfer in porous media has been extensively investigated and studied numerically due to many important applications such as geothermal engineering, chemical reactors, hydrogeology, heat pipes, solid matrix heat exchangers, and building thermal insulation. In the classical theory of porous media, a local thermal equilibrium between the fluid phase and the solid phase is assumed, the fluid and solid temperatures reach an equilibrium temperature value rapidly. However, there is a problem of using a local thermal equilibrium in porous media, because the rate of heat transfer between the fluid and solid may not be fast enough to achieve a local thermal equilibrium (LTE) due to their thermal diffusion properties. Therefore, this paper will present the importance of using Local thermal Non-Equilibrium (LTNE) modeling in heat and moisture transfer in porous media. The present review of the literature shows that currently there exists wealth information gained by the various LTNE analyses, we conclude that LTNE is more precise than LTE to study the interface thermal convection through porous media. Although we found that, there is still lack of information on hygrothermal non-equilibrium especially within bio-based insulation materials. In this case, it is important to analyze a substantial increase in heat-removal capability inside bio-based insulation material more particularly for high solid-to-fluid thermal conductivity ratio.*

MOTS-CLÉS : *Matériau poreux, Modélisation, Hors équilibre, Transfert de chaleur*

KEY WORDS: *Porous Material, Modelling, Non-equilibrium, Heat Transfer*

1. Introduction

Energy saving is of primary importance in the design of heat exchangers, it is now well known that heat convection can be enhanced through porous using material. From the point of view of the thermal equation, there are two major simulation models to analyze the thermal performances of porous media; the first one is called Local Thermal Equilibrium (LTE) model, LTE is used when the fluid phase and the solid phase are assumed in to be at the same temperature at any location in the porous media, this model is simplified theoretical and numerical research and valid as long as boundary conditions are constant [GAN 18]. However, heat transfers are unsteady in porous media and contrary to the mean temperature assumption of LTE because of the temperature difference may not be small in reality, therefore the use of LTE model leaving a few problems. In recent years more attention has been paid to the models called Local Thermal Non-Equilibrium (LTNE), its use has increased in theoretical and numerical research for convection heat transfer processes in porous media, this model is used when a temperature difference between the fluid phase and the solid phase exists, the difference between fluid and solid phases was found to increase with a decrease in conductivity ratio or an increase in porosity [NOU 05]. Non-equilibrium means the system that is not in mechanical and thermal equilibrium with their surroundings, it may arise when the characteristic time of flow is smaller than that of mass or heat transfer. The LTNE is important in situations where the characteristic time of flow is small compared to that of mass-energy transfer, the number of interfacial areas separating the phases is low, or in the case of thermal conductivities are low.

2. State of the Arts

The LTNE model is considered as a more suitable approach modeling for porous media due to heat transfer is unsteady inside the porous media, there are two regions with different temperatures, namely, the solid and fluid phase temperatures of the porous region and the fluid temperatures of the fluid region. The temperature difference between the solid phase and the fluid phase was assumed because of the large difference of the thermal conductivity between the solid phase and the fluid phase [LIN 13], hence the thermal resistance of the fluid phase is much larger than that of the solid phase. The LTNE approach is based on energy balance on both phases of fluid and solid. Under LTNE conditions, the temperatures for a solid phase in an isotropic and homogenous porous medium in the absence of internal heat generation are given by the following heat equations based on. Equations thermal non-equilibrium involving distinct energy balances for both the solid and liquid phases, and also it requires a parameter called the heat transfer coefficient between the fluid and solid material [SAI 05]. Macro-scale energy balance equations for all three phases (wetting fluid phases, non-wetting fluid phases, and solid phases) were obtained by averaging pore-scale energy balance equations. The fluid flow and heat transfer at micro and nano-scales derived with the viscous dissipation was analyzed by Buonomo b et al.[BUO 16], They conclude that the heat transfer at channel walls is enhanced due to an increase in the bulk heat transfer in the porous medium with the assumption of bio-based material is homogenous, isotropic, and saturated with the low-conductivity fluid.

The configuration of the porous media in the pipe can have a substantial effect on the rate of heat transfer. Inserting porous material in a channel could increase the Nusselt number up to 50% of that in a clear channel. The enhancement of heat transfer using porous material depends on the ratio of the effective thermal conductivity of the porous medium to that of the fluid. Most works on convective heat transfer in porous media have assumed laminar fluid flow [MAH 14]. The rate of heat transfer in porous media could be enhanced with porous media partially filling the core, it has the advantage of an increase in the Nusselt number and a smaller increase in the pressure drop. There are three general types of interfacial conditions between a porous medium and a fluid layer; the interface between two different porous media, the interface between a fluid region and a porous media, and the interface between an impermeable medium and a porous medium. The study from Yang et al. proves that a model with producing the largest value of Nusselt number when the heat transfer between the fluid and solid phases at the interface is large enough, their temperatures are equal at the interface [YAN 11], which means this model corresponds to more active convection.

Heat transport in porous media can be described and simulated in continuum mechanics by using different models, which should be suitable to different conditions, such as initial and boundary conditions, the properties of fluids and solids matrix, fluids flow characteristics, and so on. Mass and energy are transferred across phase-interfaces, and they are highly dependent on interfacial areas, at least, as long as local equilibrium is not reached. The porous materials under non-equilibrium modeling are affected by an altered form of the uniform heat flux condition at the boundaries. A thermal boundary condition model at the boundary adjacent to an impermeable wall was developed for the LTNE model for convection heat transfer in porous media. However, either experimental studies or numerical experiments are needed to determine the excess surface heat transfer coefficient in porous media.

The thermal boundary conditions at the interface between an impermeable wall and a porous medium with the LTNE model are influenced by many factors, including the impermeable wall thickness, the contact conditions, the flow field, and the thermal conductivity ratios between the impermeable walls and the two phases. [OUY 13]. A study by Abdedou et al. investigate the LTNE models by comparing two criteria in force convection through a porous channel. The first criteria is based on the maximum local temperature difference between the solid and fluid phases, while the second is based on the average of the local differences between the temperature of the solid phase and the fluid phase, they found that the parameters range corresponding to the local equilibrium validity depend on the selected local thermal non-equilibrium criteria [ABD 15].

3. Discussion & Conclusion

LTNE model is more complicated compared to the LTE model in solving two equations and defining more parameters; interfacial heat transfer coefficient (h_{sf}) and specific surface area (a_{sf}). In some cases, the LTE model also could be used in microchannel heat sinks with high porosity and at high air velocity (more than 3 m/s). As of showing in Figure 1. The average of Nu in both models is increased as the air velocity is increased, Nu by LTE models is over-predicts compared to the LTNE models at low velocity [LIN 13]. The LTE models also produce unrealistic prediction compared to LTNE in order to investigate liquid-vapor phase change inside porous media [ALO 17]. The LTNE modeling is suitable for analyzing heat transfer in porous materials because the local temperature difference between the solid and fluid phases can substantially influence the heat transfer process. It proves by Ouyang x et al. by analyzing thermal developing flow with porous media using the LTNE for different fundamental models the analytical solutions are in excellent agreement with the numerical results [OUY 13].

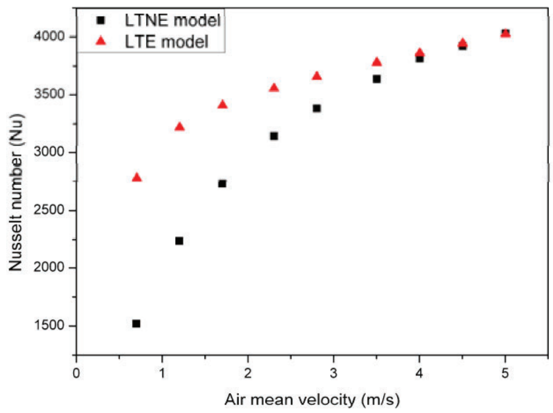

Figure 1. *A comparison of Nusselt number between LTE model and LTNE model* [LIN 13]

Porous media provided with high thermal conductivity are an adequate method of heat transfer enhancement due to their large surface area to volume ratio and intense mixing of the flow. Increase the porosity leads to an increase in the temperature difference between the fluid and solid phase, with a decrease in conductivity ratio. There is a study about the two-equation model for porous media based on LTNE between the fluid and solid phases to describe the rapid heating of living biological tissues as a porous medium, one for the tissue (solid phase) and the other for the blood (fluid phase) [MON 17].

Among of the porous media as thermal insulation today is called bio-based Material, it is the material that comes from nature with a very low negative impact to the environment, and a renewable source for the future development. The present review of literature shows that currently there exists a wealth information gained by the various LTNE analyses, however as we conclude that LTNE is more precision to LTE than we will use LTNE modeling to study the interface thermal convection through porous media, there are still being challenged by sophisticated nature of the porous bio-based materials. We found that there is a lack of information on the study of heat and moisture transfer mechanism with LTNE assumption in insulation panels using bio-based materials. For the future study, we should involve non-equilibrium modeling in bio-based materials is to analyze a substantial increase in heat removal capability inside bio-based insulation material more particularly for high solid-to-fluid thermal conductivity ratio of the porous medium, and in the end, the LTNE should be solved numerically by a computational procedure for determining the convective coefficient of heat exchange between the porous substrate and the working fluid for a porous medium.

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