CHAPTER 1. INTRODUCTION

The range of scientific and industrial applications of fluid flow and heat transfer associated with either complete or incomplete liquid-vapor phase change process inside porous media is extremely broad and hence in many engineering disciplines, one has almost no difficulty in finding a process, associated with phase change. The vastness of this realm can only be partially explored through a brief discussion of the related recent and ongoing research on the phase change process inside porous media. Therefore, this chapter provides an introduction to the research subject, together with a thorough literature review on the history and development of the related research. Moreover, the chapter outlines the main purpose and the scope of the investigation, presented in this thesis.

1.1. Research Topic, Relevance and Motivation

Phase change problems within porous media arise in a substantial number of scientific and engineering applications for the past four decades. This interest stems from the complicated and interesting phenomena associated with energy transport within the solid matrix. Furthermore, the attractiveness of porous media lies in the contemporary and wide applications available today, which have led to numerous investigations in this area. Examples include safety and post-accident analysis of nuclear reactors [1 – 6], disposal of high-level nuclear wastes [7, 8], packed-bed reactors [9], enhancement of condensation [10, 11], thermal (latent) energy storage [12], porous heat pipes [13, 14], drying equipment [15], heat and moisture transfer in insulation materials [16], oil reservoir engineering [17 – 20], and geothermal systems [21 – 23]. Moreover, a number of complex interacting transport phenomena may take place in non-isothermal multiphase systems. Most often, multiphase flows inside porous media are driven by a complex interaction of gravitational, capillary and viscous forces [24, 25].

A typical example, where complete phase change inside porous media takes place is the humidification of air. In order to humidify dry air to the desired relative humidity, super-heated steam is often added at a measured quantity with a known degree of super-heat. The typical requirement for steam flow rate for such applications is generally quite low. For this purpose, if sub-cooled liquid water is heated inside a pipe by electric heaters, boiling takes place only close to the pipe wall and hence a layer of vapor film is formed over them. Since the thermal conductivity of steam at saturation condition (100°C) is considerably lower than that of the liquid water, this vapor layer acts as the insulation to the heat flow. Therefore, the liquid flowing through the core region continues to remain sub-cooled and an inhomogeneous mixture is obtained at the pipe outlet. In order to obtain a homogeneous mixture at the pipe outlet, a mixing chamber may be used, although it could be extremely difficult to accurately control the degree of super-heat in such a process. A technological alternative, therefore, could be to realize the complete phase change process inside a duct filled with a porous medium. The higher thermal conductivity of the solid matrix of the porous medium facilitates heat transfer from the duct periphery to the core such that the fluid is more or less uniformly heated. The degree of super-heat, however, depends on several parameters, such as, applied heat flux, mass flow rate, inlet temperature, properties of porous media, etc. Therefore, in order to have a better understanding and hence precise control over the phase change process, accurate predictions are required. However, difficulties in numerical simulations occur mainly due to the strongly nonlinear nature of governing equations and constitutive relations. Moreover, as will

be shortly apparent in chapter 2, discontinuities in the modeled thermo-physical properties at phase change boundaries also pose a major challenge. Determining a remedy for this problem is the main objective of the present work.

1.2. History of Modeling Two-Phase Flow in Porous Media

Liquid-vapor phase change process inside porous media is encountered in diversified scientific and engineering applications [25]. The theoretical basis for solving such problems essentially rely upon the traditional Separate Flow Model (SFM) [17, 18], where the liquid and the gaseous phases are considered as two distinct fluids with different properties, that generally assume different velocities, satisfying separate set of conservation equations. In this respect, the complete phase change process within porous media could be characterized by the presence of three distinct regions: sub-cooled, two-phase mixture and superheated vapor regions. Since SFM is most often extremely complex and perhaps inconvenient for the direct use in numerical simulations, Ramesh and Torrance [26 – 28] proposed the Separate Phase Model (SPM) in order to solve heat transfer problems involving boiling in presence of natural convection in a fluid-saturated porous medium for each of these regions while continuously tracking the interface between them using a moving boundary approach. For practical applications, however, SFM (or SPM) is considered inconvenient for numerical implementation since it requires tracking of the interfaces using a moving boundary approach and the presence of large number of coupled nonlinear equations.

Recognizing the complexities and the inherent problems of SFM (or SPM), Wang and Beckermann [29] proposed the Two-Phase Mixture Model (TPMM) based on enthalpy formulation for the phase change process through capillary porous media, where the separate phases are considered as the constituents of a binary mixture. This model is characterized by the coexistence of a two-phase zone and single-phase regions with irregular as well as moving interfaces lying in between them. The solutions could be obtained on a fixed grid, without requiring a priori knowledge (tracking) of the phase boundaries, that could be irregular in space as well as moving in time. These formulations essentially rely upon the traditional SFM and hence do not require invoking any additional assumption. The associated conservation equations for TPMM are derived specifically for addressing the phase change problems inside porous media. Based on the enthalpy values of the mixture, the state of the system inside the porous media has been identified. The inherent assumption in this model has been that the two-phase region is at a constant temperature (equal to the boiling temperature of the liquid) and hence phase change is taking place between the interfaces of the two-phase and the single phase regions. As explained latter in chapter 2, Wang et al. [30] first identified that the original formulation of Wang and Beckermann [29] is not readily suitable for numerical implementation owing to several reasons. Therefore, they proposed the first modification to the original model, by introducing the volumetric enthalpy as dependent variable on the temperature and liquid fraction for the energy conservation equation, and presented a study on boiling and natural convection in a porous layer heated from below. Later, Wang et al. [31] examined this model numerically for transient natural convection and boiling in a porous layer heated from below. Wang and Beckermann [32] then performed a numerical study on pressure-driven two-phase flow along vertical plate in a capillary porous medium as a complement to the previous work of Wang and Beckermann [29]. In their study, full two-phase similarity solutions have been obtained for both boiling and condensing flow. They observed that the boiling boundary layer has been normally wider than the one in condensing flow.

However, a closer look into the TPMM of Wang et al. [30] reveals that since some of the mixture variables and properties remain undefined for the superheated vapor phase, it cannot be employed for the prediction of complete phase change process, where phase change takes place from the sub-cooled liquid phase to the superheated vapor phase. In order to eliminate this drawback, Wang [33] proposed the second modification of TPMM [29], by introducing the modified volumetric enthalpy as dependent variable for the energy conservation equation. Nevertheless, all versions of TPMM are characterized by the coexistence within a two-phase zone, separated by the irregular as well as moving interfaces (for transient problems) of single-phase (either liquid or vapor) regions. Since these variants are obtained for fixed numerical grid, unlike SFM or (SPM), there is no requirement for the complex as well as time consuming interface tracking. Possibly owing to the generality and the ease of numerical implementation, the TPMM of Wang is by far the most widely used method for the simulation of phase change process inside porous media. In this respect, several researchers have been adopted the TPMM of Wang for simulating phase change problems under different flow conditions in order to enhance the knowledge of two-phase flow inside porous media. A further careful look into the formulation also reveals that the available formulations are valid only for Darcy flow inside an isotropic porous media [29 – 33]. Although the initial propositions of TPMM [29, 30, 33] are applicable only under the assumption of Local Thermal Equilibrium (LTE) condition, it has been extended in order to accommodate the more general Local Thermal Non-Equilibrium (LTNE) condition. For LTNE condition, the solid matrix and the fluid medium can locally coexist at different temperatures, and the respective energy conservation equations are coupled to each other through the volumetric heat exchange term.

1.3. Review of Literature and Related Work

Phase change problems inside porous media using either the forced or natural convection have attracted numerous researchers due to its implications in a wide set of technological applications. The effects of forced and natural convection on the phase change process within porous media have been studied experimentally and numerically. Thus, the following subsections provide a literature review of the previous experimental and numerical work related to the phase change process inside porous media.

1.3.1. Experimental Work

As compared to the numerical investigations, experimental studies in the field of phase change inside porous media are considerably less in number, possibly owing to the difficulty in acquiring reliable data. Udell [34], for example, obtained theoretical and experimental results for boiling within a rectangular cavity filled with a porous medium, which was heated on one side. The effects of capillarity, gravity forces, and phase change have been included. Theoretical results showed excellent agreement when compared with the experimental data. In the study, the heat transfer was increased several orders of magnitude beyond pure conduction due to evaporation, convection and condensation phenomena similar to conventional heat pipe operation. Later, Easterday et al. [35] reported experimental and numerical results for the two-phase flow and heat transfer in a horizontal porous formation with water flow and partial heating from below. In their study, experimental results have been also attained to measure temperature distributions and to visualize the two-phase flow patterns. Partial agreement between experimental and numerical

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results has been achieved. A combined experimental and numerical study has been providing new insight into conjugate single and two-phase flow and heat transfer in porous media. Numerical results have been obtained based on the TPMM of Wang et al. Their results showed that the two-phase structure and flow patterns are strongly dependent upon the water inlet velocity and the bottom heat flux.

Peterson and Chang [36] performed an experimental study on two-phase heat dissipation in high-conductivity porous channel heat sinks, where sub-cooled water has been used as the working fluid. The experiments have been conducted for different porous channels sizes and have been fabricated using sintered copper particles inside rectangular copper channels. The experimental results were compared to the results predicted using numerical modeling. Their results indicated that the high thermal conductivity of the porous material and the large solid-fluid contact area combined to create a highly effective, two-phase heat sink which may provide an effective mechanism for cooling high heat flux microelectronics. Zhao et al. [37], on the other hand, carried out an experimental investigation on the buoyancy-induced flow of water associated with the phase-change heat transfer inside a vertical porous tube that is heated at the wall with a constant heat flux. Their results showed that the diameter of the porous tube and the particle size of porous media have significant influence on the amount of vaporized mass of the fluid. Chen et al. [38] performed an experimental study on boiling heat transfer inside channels packed with particles having a bimodal size distribution (sintered copper bi-dispersed porous media). Their results indicated that the porous material is a highly effective two-phase heat sink that offers a lower flow resistance as compared to that of the mono-dispersed porous materials of same pore diameter.

Later, Zhao and Liao [39] conducted an experimental and theoretical modeling study on evaporative heat transfer characteristics of a capillary porous structure heated with a permeable heating source on the top. The experiments have been tested for three different typical conditions according to its heat flux. Their results showed that for small and moderate heat fluxes the whole porous structure became fully saturated with liquid except for adjacent to the horizontal heated surface where evaporation took place uniformly. For higher heat fluxes, a two-phase zone developed in the upper portion of the porous structure, while the lower portion of the porous structure became saturated with sub-cooled liquid. Theoretical results showed that the model is in good agreement with the experimental data. Yuki et al [40] verified experimentally the possibility of extremely high heat flux (over 70 MW/m^2) removal for various porous materials. The experiments have been conducted for two different porous media materials (bronze particle-sintered and copper fibers-sintered) which have high thermal conductivity to enhance the thermal diffusion in the porous material. In their study, constant heat removal against local inlet heat flux of over 70 MW/m^2 has been observed by using the bronze porous medium with high thermal conductivity. Furthermore, the evaluation of heat removal performance for various porosities and particle diameters of copper fiber porous media have been clarified, and the lower porosity material has been found to be useful for improving the evaporation rate inside porous media.

Later, Yuki et al [41] clarified experimentally and numerically the key issues to enable extremely high heat flux removal exceeding $10 \, \mathrm{MW/m^2}$ of two-phase flow in particle-sintered porous media. The experiments have been also carried out for two different types of porous media (stainless steel particle–sintered and bronze particle–sintered packings). For the experiments, the

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effects of porous structures such as pore size and porosity on the heat transfer characteristics under some heat flux inputs have been investigated. The results suggested that liquid-vapor exchange due to capillary and pumping effects works effectively under several MW/m^2 in this cooling system. On the other hand, the TPMM of Wang along with LTE assumptions have been used for numerical simulation of two-phase flow inside porous media in order to evaluate what kind of porous material is appropriated for higher heat removal. The results showed that utilizing a higher thermal-conductivity matrix facilitates a delay in the onset of the phase change near the heating wall and leads to much higher heat flux removal, even at the same liquid saturation, compared to the case utilizing a lower thermal-conductivity matrix. Recently, Li and Leong [42] performed an experimental and numerical investigation in order to investigate the flow boiling characteristics of water and FC-72 inside aluminum foams. With the help of their experiments, the heat transfer process prior to the onset of nucleate boiling and the hysteresis effects have been investigated. The Brinkman–Forchheimer model, along with Local Thermal Non-Equilibrium (LTNE) assumptions has been adopted for the single-phase simulations, while TPMM of Wang [33] has been employed for the two-phase predictions. Their results demonstrated reasonable agreement between the numerical and the experimental data.

1.3.2. Numerical Work

Numerical simulations can provide useful information in such complex systems with phase change processes inside porous media, and they are considered very helpful in supporting the engineering design. In many industrial applications sub-cooled water injection is commonly used in porous evaporators. Coolant phase change occurs in the solid matrix. During a complete phase change process, three distinct regions, namely, sub-cooled liquid, two-phase mixture and superheated vapor regions could be observed inside an evaporator fitted with a porous medium. The development of efficient evaporation process relies heavily on numerical modeling. This is a complex and consuming task since high nonlinearities in the problem formulation may lead to very sharp thermal and saturation fronts. Because of these rapid variations of physical quantities across the fronts, special treatment must be applied in order to achieve reasonable accuracy. The problem of modeling heat and mass transfer in a single-phase fluid flowing through a porous medium is somewhat challenging. A significantly more complicated modeling problem concerns the motion of a fluid through a porous structure which undergoes a phase change. The evaporation process has been classified as such a problem. Fluid phase change in porous media is also at the center of many technological problems. In configurations involving condensation and evaporation, regions of single-phase flow and two-phase flow often coexist within the porous medium. As far as the phase change process inside porous media is concerned, extensive studies have been carried out in the past and performed under different flow condition depending on the desired information and computational limitations.

Waite and Amin [43] used the TPMM of Wang et al in order to study the transient fluid flow and heat transfer mechanisms of two-phase flow in a side heated porous enclosure numerically. In their work, numerical results have been compared with the experimental data with good agreement. Furthermore, steady-state and transient temperature distribution as well as fluid motion have been presented for a wide range of Rayleigh numbers, imposed side heat flux on the vertical wall and fluid velocity at the bottom boundary. The observed results for certain values of the above

parameters indicated bi-cellular convective flow of the fluid. Several other researchers [44 – 52, 55, 56], on the other hand, used the TPMM of Wang for the simulation of phase change process under different flow conditions inside porous media. Zhao and Liao [44] numerically investigated mixed convection boiling inside a vertically oriented capillary porous structure with asymmetric heating condition at opposing walls. In their study, different flow directions have been investigated. Liquid saturation, temperature, liquid and vapor velocity fields subjected to both superimposed aiding and opposing flows have been analyzed and presented for different values of inlet velocity. Their results showed that the direction of the incoming fluid have great influence on both the flow field and temperature distribution. Zhao et al. [45], on the other hand, conducted a numerical study on the buoyancy assisted phase change process in a symmetrically heated vertical porous channel. Their results showed that the mass flux increases as the applied heat flux is increased for both single and two-phase flow with rather low vapor fraction. However, the numerical results also indicated that the induced mass flux drops drastically and remains approximately constant afterwards when the vapor fraction is increased. Furthermore, this result was agreed qualitatively when compared with experimental data of Zhao et al. [37].

Although steady-state investigations can provide understanding of the physics behind two-phase flow problems, the transient simulation approach would be more useful since it reveals the evolution of the boiling process and the interactions between the liquid and vapor phases. In this regard, Najjari and Nasrallah [46] conducted a numerical study for the transient flow boiling with mixed convection in a vertical porous layer with localized heating from one side when the liquid is injected at the top face. In their study, temperature, pressure, velocities of the fluids, and evaporated volume fraction have been presented and analyzed for different time-space evolutions. Further, the effects of the inlet velocity, imposed heat flux, and permeability have been performed. Numerical results showed that boiling is important if the effects of both natural and forced convection are similar. Najjari and Nasrallah [47] numerically studied boiling inside an inclined porous layer, where apart from the effects of permeability and inlet velocity, different inclinations of the porous channel have been also considered. Their results showed that a critical value of the inclination angle exists which corresponds to a maximum value of the evaporated volume fraction at low inlet velocity and high permeability. Later, Najjari and Nasrallah [48 – 51] presented several case studies on the conjugate incomplete phase change problems inside a channel, with a fluid layer lying above the porous medium. They investigated the effects of distance between the heat sources, their length and the thickness of the porous layer on the complex interaction between free convection heat transfer, latent heat storage and the liquid-vapor phase change process.

An additional problem that is encountered while simulating the complete liquid-vapor phase change process (i.e., from the sub-cooled liquid phase to the superheated vapor phase) inside porous media is the occurrence of rapid, non-physical change in the predicted temperature distribution over an extremely short distance that results primarily due to the presence of the effective diffusion coefficient. Although this problem was not clearly identified in the aforementioned studies, it was remedied by Li et al. [52] who employed the "modified" Kirchhoff method [53] for calculating the effective diffusion coefficient at the control volume (CV) faces to investigate the transient behavior of two-phase flow inside porous media. The performance of this method and the conventional harmonic mean approximation [54] were compared in [52] and the former was found better in handling the rapid change in the effective diffusion coefficient. In their study, the effect of heater

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location on the fluid flow and heat transfer has been investigated. The results also showed that the liquid and vapor flow fields, as well as the temperature distribution and liquid saturation location exhibit distinctly different features for different heater locations. The modified Kirchhoff method was then employed by Li et al. [55, 56] in order to investigate different two- and three-dimensional transient phase change problems inside porous channels, considering symmetric and asymmetric heating as well as aiding and opposing buoyancy conditions. In their studies, the temperature distribution, liquid saturation location and velocity fields have been presented for different Rayleigh and Peclet numbers. The results showed that the liquid flow bypasses the two-phase zone, while the vapor flows primarily to the interface between the sub-cooled liquid region and the two-phase region.

On the other hand, He et al. [57] presented a series of new conservation equations for mass, momentum, and energy in order to describe the performances of fluid flow, heat absorption, and phase change inside porous media based on the enthalpy formulation of SFM. In their model, three additional assumptions have been considered: firstly, considering the compressibility of vapor in the momentum and energy equations; secondly, adding a term of the momentum transfer caused by liquid phase change into the momentum equations of vapor and liquid phases in two-phase region, and finally, the local thermal equilibrium (LTE) assumptions and the variation of enthalpy with temperature and pressure in the two-phase region. The model and numerical strategies have been validated with experiments. Numerical results showed that the pressure solutions are quite identical to experimental data. In addition, the effects of coolant injection rate and external heat flux on the distributions of temperature, pressure, and velocity have been discussed by using the validated model.

As far as the energy conservation equation for porous media is concerned, two separate models, suitable for different applications, are available according to the homogenization approach: the Local Thermal Equilibrium (LTE) and the Local Thermal Non-Equilibrium (LTNE) models. Both these models can be applied for the complete phase change process inside porous media based on the TPMM of Wang. As the name suggests, under the assumption of LTE, the heat exchange between the working fluid and the solid matrix of the porous medium is neglected [44 – 52, 55 – 57]. On the other hand, in order to consider the internal heat transfer between the fluid and the solid phases, the LTNE model has to be applied, where two separate energy conservation equations for both phases are solved. These two equations are, however, coupled to each other through the volumetric (convective) heat exchange term that takes care of the local energy transfer from the solid phase to the fluid phase and vice-versa. For single-phase problems, Wang and Wang [58] performed an investigation in order to quantify the error caused by the LTE assumption, where, in principle, LTNE model should have been employed, although, they did not comment on the applicability of LTE model for two-phase problems. Nevertheless, the use of the LTNE model is quite common in many other applications of porous media, such as, combustion inside porous media [59 – 61], where the difference between the solid and the fluid temperatures could be substantially high, particularly close to the flame-front, which cannot be neglected in order to explain the mechanism of internal heat recirculation. According to Jiang and Ren [62], the classical LTNE model was first presented approximately 80 years ago. In recent years, however, serious attention has been paid to the LTNE model for such prediction since it is more realistic for the description of underlying physical phenomena associated with the local energy transfer and hence it

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helps in better understanding of the mechanisms responsible for the overall heat transfer during the phase change process inside porous media [63 – 70].

Taking the internal heat exchange between the solid and fluid phases into account, Peterson and Chang [63] employed the TPMM of Wang et al along with the assumptions of the LTNE model in order to numerically investigate the phase change process from sub-cooled liquid to the saturated mixture in a high conductivity porous channel used as a heat sink. Their results indicated that the high thermal conductivity and large solid-fluid contact area of the porous channel produce a high heat transfer performance associated with two-phase heat dissipation, which may serve as a viable alternative to the existing cooling techniques for microelectronics applications, characterized by high operating heat flux. Yuki et al. [64] modified the TPMM of Wang by applying Ergun's law and the LTNE model instead of a one-energy model in order to investigate the thermo-fluid flow characteristics under high flow velocity in porous media. Their study showed that the modified equations produced more realistic and reasonable results for the two-phase flow under high velocity and high heat flux. It has been also shown that heat sinks made of porous media with high thermal conductivity and large surface area can improve heat transfer performance greatly. Furthermore, numerical results showed that in a single phase flow, the degree of thermal non-equilibrium has a positive correlation with increasing flow velocity and heat flux input, whereas in the two-phase flow, the degree of thermal non-equilibrium is remarkable in the two-phase region.

More recently, Shi and Wang [65] presented a LTNE model based mainly on the TPMM of Wang in order to investigate the transpiration cooling problems with coolant phase change within porous media. In their work, the effect of mass flow rate, heat flux, thermal conductivity, porosity, sphere diameter of the porous matrix and pressure on the temperature and liquid saturation distributions have been investigated. Numerical results showed that the effect of the transpiration cooling would be limited under high pressure due to a smaller size of two-phase region. Further, this investigation also discovered an inverse phenomenon, namely in the two-phase region, where coolant temperature could be higher than the solid temperature. Later, Xin et al. [66] numerically simulated the processes of liquid coolant flow, heat absorption, and phase change within Micro-channels, which were heated at one side by given heat fluxes in order to investigate the ability to dissipate large amounts of heat flux using TPMM. In addition, the pressure and temperature distributions obtained at different conditions have been exhibited and analyzed. Numerical results indicated that the trends predicted by this approach agree well and the modeling has been validated in some sense. Furthermore, countercurrent flows in two-phase region near the transition point have been observed.

Nevertheless, in the literature mentioned above based on the LTNE model, the coupled momentum and the energy equations have been solved separately, and neither the effect of density and pressure variations caused by phase change on the enthalpy nor the influence of varied thermal physical properties on the momentum equation have been observed. This is because these models have been based on two assumptions: the saturation temperature is constant in two-phase region and the enthalpy is only a function of temperature. As currently discovered by Wei et al. [67], these two assumptions could lead to non-veracious phenomenon in numerical simulation (i.e., a thermal insulating layer appearing within the porous matrix, which is not real because the solid matrix is made of the metal with high thermal conductivity). In order to avoid the non-veracious

phenomenon, Wei et al improved the mathematical formulation of the transpiration cooling problems with boiling which is based on the Gibbs free energy of the liquid and vapor phases being equal in the two-phase region. The LTNE model and the variation of enthalpy with temperature and pressure in the two-phase region based on the TPMM of Wang have been considered. The temperature variations of the fluid and solid phases, the liquid saturation, and the pressure of the fluid within porous media have been investigated. Numerical results showed that the temperature field of the fluid and solid phases, the liquid saturation, and the pressure of the fluid within porous media are consistent, and the non-veracious issue of the thermal insulating layer has been successfully resolved. In addition, numerical study was limited for incomplete phase change process, although the mathematical formulation could be used for the simulation of complete phase change process.

Lindner et al. [68] conducted a study on multiphase flow in a porous channel with local heat input from one side. In their study, the LTNE model has been used to investigate fluid flow and heat transfer with phase change inside porous media. The effect of gravity, Stanton number of evaporation, Rayleigh number, Peclet number, and Biot number on fluid flow and heat transfer under steady-state condition for both aiding and opposing flows have been investigated. Numerical results showed that for sufficiently high heat input, opposing flow yields large differences in position of the biphasic zone and minimal liquid saturation. Furthermore, the minimal saturation increases with increasing Stanton number, Peclet number or Biot number. The Rayleigh number has an opposite effect on the minimal saturation. Xin et al. [69] developed a Modified Separate Flow Model (MSFM) to numerically investigate the heat and mass transfer with phase change behaviors in porous media. In their model the effects of capillarity, liquid phase change, non-isothermal two-phase region and the LTNE assumption have been considered. Two typical numerical examples with a one-dimension model of porous media have been studied that the high heat fluxes are vertical and parallel to the fluid flow direction, respectively. Numerical results showed that the influence of heat flux direction on heat and fluid flow behaviors in porous media is large. Furthermore, the non-isothermal assumption in the two-phase region is obvious for the former while the LTNE assumption is remarkable in the two-phase region for the latter.

A comprehensive review dealing with various aspects of the field of evaporation within porous media, have been well documented in several articles [6, 15, 22, 25] and books by Nield and Bejan [70], Kaviany [71], Vafai [72], Ingham and Pop [73], and Vadasz [74] to name a few. Interested readers should refer to them for an excellent overview. However, most of these studies as well as those mentioned in the foregoing section have been focused on homogenous and heterogeneous isotropic porous media in the steady-state solution within the frame work of one- and two-dimensional descriptions. Only in some of the investigations, the transient simulation from a single (liquid) phase to two-phase mixture region has been discussed.

A careful review of the literature reveals that almost all previous studies dealt with incomplete phase change process (i.e., from the sub-cooled liquid to the two-phase mixture) using LTE and LTNE models. According to the best of the author's knowledge, other than the investigations of Wang [33], Shi and Wang [65] and Lindner et al. [68], there is no study that dealt with the phase change process from a sub-cooled liquid state to the superheated vapor state inside a porous medium, where the phase change takes place without any appreciable change in pressure. Hence,

the saturation temperature remains the same during the complete phase change process. This assumption applies when the pressure drop through the evaporator is negligible compared to the static pressure for a given saturation temperature, which is valid for low mass flow rate applications. While Wang and Lindner et al dealt with a two-dimensional problem with a localized heater using LTE and LTNE models, respectively, Shi and Wang obtained results with a one-dimensional formulation under the LTNE condition. Nevertheless, in their studies, although the formation of superheated vapor could be numerically predicted, they are also associated with a very high temperature change within an extremely short distance. For instance, Wang presented results for porous media, composed of steel and glass beads, and reported $100^{\circ}C$ to $500^{\circ}C$ temperature difference, respectively, between two successive isotherms in the superheated vapor region, located extremely close to each other. Wang identified this zone as the dry-out region, although its existence could not be experimentally substantiated since they have been carried out only for phase change from the sub-cooled liquid to the two-phase condition. In the LTNE model of Shi and Wang, owing to the presence of volumetric heat exchange term, uniformity of temperature could be better ensured. This means that even if the predicted fluid temperature became extremely high during iteration, immediate energy transfer to the solid phase would possibly lower the fluid temperature to realistic value. Nevertheless, they also observed a very high temperature change within a very short distance in the vapor phase. Furthermore, a careful examination of results, presented by Lindner et al also shows the occurrence of a temperature difference at the interface between solid and fluid phases at the wall with a magnitude from $15^{\circ}C$ to $300^{\circ}C$ and a maximum temperature up to $1600^{\circ}C$. Such a maximum temperature is higher than the melting point of bronze, which is $913^{\circ}C$. Such apparently unrealistic predictions may be attributed to discontinuities in the modeled effective diffusion coefficient and effective heat capacity ratio.

Wang did not recognize the rapid change in the predicted temperature over an extremely short distance as a non-physical "jump" and hence could not identify the specific reason. In the present work, it is pointed out that the non-physical jump in the predicted temperature distribution occurs due to the rapid change (discontinuity) in the effective diffusion coefficient close to the interface between the single- and two-phase regions. The discontinuity shall henceforth be referred to as the "jump" in the remainder of the thesis. It may be noted here that the term "jump", used in the context of the present study, has no relation to the physical density "jump" condition used in Volume of Fluid (VOF)-like methods. Nevertheless, Li et al. [52] possibly first recognized the presence of discontinuities in the modeled effective diffusion coefficient and suggested special treatment for this term. Although they proposed two different numerical schemes to avoid the "jump" in the predicted properties across interfaces, only the phase change process from the sub-cooled liquid phase to the two-phase mixture was considered in their study. In the scope of the present work, it has been attempted to extend suggestions from Li et al for simulations of phase change process from the two-phase mixture to the superheated vapor phase, but generally remained unsuccessful. The occurrence of "jump" in the predicted temperature distributions could also be avoided by assuming the saturation enthalpies ($h_{l,sat}$, $h_{v,sat}$) and the latent heat (h_{fg}) to be functions of the saturation pressure [57, 67 , 69, 75], thereby allowing explicit heat diffusion to occur solely due to the temperature gradient even in the two-phase region (since the saturation temperature depends on the local pressure). Such a remedy, however, may not perform equally well for cases where the pressure gradient is negligible owing to the extremely low mass flow rate, as in the case of present

application, where the saturation temperature remains the same during the complete phase change process.

It will be evident in chapter 2 that the effective diffusion coefficient is exactly equal to zero in the two-phase region for liquid saturations $s = 0$ (fully vapor) and $s = 1$ (completely liquid) since the phase change takes place without any appreciable change in saturation temperature, whereas it remains constant for purely liquid and vapor phases owing to the assumption of constant thermo-physical properties in the single phase regions. Thus, sharp discontinuities exist in the diffusion coefficient across interfaces between single and two-phase regions that are also more severe close to the vapor phase. Such a situation often leads to a non-physical "jump" in the predicted temperature. An additional problem might also occur due to the huge difference in densities of liquid and vapor phases [33] that leads to substantial increase in velocity during phase change in a constant cross-sectional area duct, e.g., water at its saturation temperature (100°C), the liquid density (957.85kg/m^3) is nearly 1600 times that of the vapor (0.5978kg/m^3). A dedicated effort is, therefore, required in order to suggest the remedy for such occurrences and hence the present study is devoted towards resolving this issue using different models which guarantees that no "jump" occurs in the predicted temperature distribution during numerical simulation of complete phase change process inside porous media.

1.4. Research Objectives

Concerning the literature review presented above, it can be noted that some of the specific features of phase change processes are not clarified and require further investigation, such as characteristics of the complete phase change processes inside porous media, e.g., due to the previously mentioned large discontinuity in modeled effective diffusion coefficient and effective heat capacity ratio. Therefore, the present work aims to develop useful tools using numerical methods in order to perform a numerical study of the complete liquid-vapor phase change process inside porous media. In the first phase of this study, a two-dimensional numerical code has been developed by adopting the existing TPMM of Wang on orthogonal coordinates. This development allows for the simulation of the phase change process within porous media in both channels and pipes of constant cross-sectional area in the axial direction, while considering the densities in the single phase regions to be constant. The numerical code has been verified by comparing the simulated results with the existing numerical results for other researcher under the same condition for partial phase change process. The proposed research work shall deal with modeling and simulation of the complete phase change processes inside porous media. Thereby, the next phase of the research work is to propose a new method (smoothing algorithm) for dealing with sharp discontinuities in the modeled effective diffusion coefficient for the simulation of complete phase change process inside porous media. In order to demonstrate the effectiveness of the suggested remedy, the complete phase change process of liquid water for a one-dimensional flow situation through a constant cross-sectional area duct, filled with a porous medium has been considered. However, it will also be evident in chapter 2 that the suggested remedies are easily extendable for multi-dimensional problems involving any phase-change fluid. The outcome of this research effort is the modification approach that enables one to avoid non-physical "jump" in the predicted temperature distribution across interfaces during numerical simulations.

In this respect, the proposed investigation is expected to considerably advance the present knowledge by allowing the simulation of the complete phase change process inside porous media. The results of this work shall lead to more realistic predictions required for the description of the underlying physical phenomena associated with the local energy transfer and hence a better understanding of the mechanisms responsible for the overall heat transfer during the phase change processes inside porous media. The proposed investigation has addressed various distinct issues, pertinent to the complete phase change processes inside porous media in order to examine further the proposed smoothing algorithm for the effective diffusion coefficient that are elaborated in the following:

1. The existing formulation has been applied in order to accommodate the effect of the smoothing algorithm under LTE assumption for the simulation of complete phase change processes in both channels and pipes of constant cross-sectional area in the axial direction.

2. An alternative formulation is proposed, where the enthalpy of the phase-change fluid is treated as the dependent variable in the energy conservation equation, in order to remove the complexity in the original formulation of Wang and Beckermann for efficient numerical simulation of complete phase change process inside porous media. In the subsequent text of the present thesis, the newly proposed modification shall be referred to as the "modified enthalpy formulation". In order to demonstrate the consistency and the accuracy of the proposed formulation, one-dimensional complete liquid-vapor phase change problem of liquid water inside a constant cross-sectional area porous evaporator with known properties has been considered by employing two different heating conditions at the evaporator wall.

3. In practical situations, however, the thermal conductivity of the solid matrix of porous media is substantially higher than that of the working fluid. As a result, the heat that is added at the duct surface is transferred to the core of the evaporator mainly through the solid struts. Particularly in the phase change region, where the fluid remains constant at the saturation temperature owing to the thermodynamic constraints, heat conduction through the solid medium plays an important role in the energy transfer process from the heated wall. The temperatures of the solid phase and the fluid medium differ from each other, although the difference in temperatures may small but substantial owing to the extremely high heat exchange coefficient between them, resulting from the small characteristic pore diameter. Most importantly, for multi-dimensional problems, the complete phase change process cannot be realistically simulated using the conventional LTE model as explained in chapter 4, owing primarily to the extremely low values of effective diffusion coefficient in the two-phase region, particularly close to the saturated liquid or vapor condition that acts as an extremely high resistance to heat transfer. For constant heat flux boundary conditions, extremely high (non-physical) temperatures are predicted at the wall/near-wall nodes. For constant wall temperature application, complete phase change cannot be realized unless the prescribed wall temperature is unrealistically high. In addition, complete phase change process cannot be simulated using LTE model for transient problems owing to the high discontinuity in the effective heat capacity ratio. In such situations, the LTNE model appears to be the more (or at all) appropriate as compared to the commonly used LTE model. In order to eliminate the drawbacks in LTE model, the present one- and two-dimensional CFD codes have been

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extended to include the effects of the LTNE model for one- and two-dimensional problems, respectively, (i.e., one-dimensional pipe flow as well as channel and pipe flow models). Therefore, the main objective of this study is to investigate the complete phase change process inside porous media using the LTNE model and TPMM of Wang by extending the smoothing algorithm for the effective diffusion coefficient.

4. Another interesting aspect of evaporation inside porous media lies in the expansion of the phase change fluid that occurs due to the huge difference in the densities of the liquid and the vapor phases. Since the vapor-phase occupies a larger volume, in order to maintain the continuity of mass flow, the velocity increases considerably in a constant cross-sectional area duct. In this situation, it may be worthwhile to use a duct with increasing cross-sectional area in the axial direction. Simulation of phase change within the porous media fitted into such a variable cross-sectional area duct would, however, require employment of curvilinear coordinates and an extension of the formulation developed so far to the body-fitted coordinate system. This implicitly indicates that the method should be extended first to the non-staggered variable arrangement. Therefore, the present CFD code has been firstly extended for non-staggered grid layout on orthogonal coordinates. The modified CFD code can be used in both LTE and LTNE models, while utilizing the smoothing algorithm for the effective diffusion coefficient in order to investigate the complete phase change process of water inside a porous channel based on TPMM of Wang.

5. For the selection of the porous media in the evaporator, a higher thermal conductivity in the radial direction is desirable as compared to that in the axial direction since this will help with conductive heat transfer from the periphery to the core of the duct. A structure made of axially compressed wire mesh can serve the purpose. Simulation of complete phase change problems within such porous media would, however, require the extension of the currently available formulation for anisotropic porous media along with the LTNE model. This applies specifically to permeabilities and thermal conductivities. In order to accommodate this aspect, the two-dimensional CFD code has been further extended to include the effects of anisotropy in the porous media properties and hence the present code is capable of handling anisotropic porous media along with the LTNE model.

6. During the complete phase change process, since the density of the working fluid decreases by several orders of magnitude, porous evaporator with increasing cross-sectional area in the flow direction may be employed in order to reduce the axial velocity and hence to increase the residence time of the working fluid inside the evaporator. In this regard, an extension of the numerical model is performed in order to include the effect of increasing cross-sectional area in the axial direction to accommodate higher volume flow rates of the vapor phase, when considering complete phase change process inside porous media. For simplicity, the complete phase change process of water for a one-dimensional flow situation through a divergent porous evaporator, based on the TPMM of Wang has been investigated.

1.5. Thesis Outline

In this thesis, the complete liquid-vapor phase change process inside porous media is numerically investigated. The present thesis is divided into eight chapters which are organized in

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the following manner. Chapter 1 of this thesis describes the applications and the background related to two-phase flow inside porous media. A briefing on previous work in this field and the aim of this study are also presented. Chapters 2 and 3 provide the mathematical formulation and numerical aspects of the current computational models. In chapter 2, the governing equations for the fluid flow describing the conservation of mass, momentum and energy, along with the expression for the mixture properties in two-phase flow and the boundary conditions inside porous media are described. The provided description details the derived formulations for all variants of TPMM [29, 30, 33] along with the LTE assumption. A newly proposed modification of the enthalpy formulation, based on the model of Wang and Beckermann, is presented in detail. Non-dimensionalization has been carried out for all the mathematical formulations. Special method (smoothing algorithm) has been developed in order to deal with the high discontinuity in the modeled effective diffusion coefficient, and is also presented in detail. Furthermore, chapter 2 describes the mathematical formulation along with the LTNE assumptions for both isotropic and anisotropic porous media. Chapter 3 gives a detailed description of the numerical discretization method presented herein using Finite Volume Method (FVM). The numerical method for solving the conservation of momentum is discussed separately using staggered and non-staggered grid layouts. In chapter 3, computational tests to verify the numerical code for relevant problems have been carried out by comparing the simulated results with the existing numerical results for other researcher under the same condition for an incomplete phase change process.

Chapters 4, 5, 6 and 7 concern the numerical results of the complete liquid-vapor phase change process inside porous media. The strategy of the proposed smoothing algorithm introduced in chapter 2 is applied in order to avoid the non-physical "jump" in the predicted temperature distribution during the numerical simulation of the complete phase change process inside porous media. Parametric study has been performed to investigate the effects of different parameters on the flow fields and temperature distribution of the complete phase change processes. Chapter 4 presents the one-dimensional results of the complete phase change process inside a constant cross-sectional area porous evaporator. Moreover, chapter 4 provides the comparison of numerical results of the complete phase change process for one-dimensional problems based on the modified enthalpy formulation with the TPMM of Wang. In addition, chapter 4 also provides the two-dimensional results of the incomplete and complete phase change process, under steady-state condition for both channel and circular pipe flow models, based on the TPMM of Wang along with the LTE model using staggered and non-staggered grid layouts. Chapter 5 provides the one and two-dimensional results of the complete phase change process, under steady-state and transient conditions, based on the TPMM of Wang along with the LTNE model by extending the proposed smoothing algorithm for the effective diffusion coefficient, for both circular pipe and channel flow models using both staggered and non-staggered grid layouts. Chapter 6 concerns the results of the complete phase change process inside a porous channel when considering anisotropy in the properties of porous media. Chapter 7 provides detailed results of the complete phase change process inside divergent porous evaporator. Finally, chapter 8 concludes the thesis, presenting a summary of the research work, the main conclusions extracted from it, and recommendations for future related investigations.

CHAPTER 2. MATHEMATICAL FORMULATION

Two phase flow in porous media typically consists of three phases: solid, liquid and vapor phases. In addition to the transport of individual phases, there is a phase change process involved inside the porous media. Treatment of individual phases using the well known point equations of continuum physics is rather complicated and computationally expensive. In order to realize numerical flow simulation employing the modified volumetric enthalpy formulation of Two-Phase Mixture Model (TPMM) [33] flow in porous media, the strategy is to identify, to understand and finally to derive the appropriate mathematical formulations, which describe the respective flow scenarios. Since these processes mostly originate from the separate flow model (SFM), this level also poses the natural starting point of general TPMM flow analysis.

Therefore, this chapter describes the general modeling procedure of TPMM applied in the present work. The major objective is to obtain a possible remedy in order to deal with the high discontinuity in both the effective diffusion coefficient and the effective heat capacity ratio that would allow to investigate the complete phase change process inside porous media. In this regard, the mathematical formulation in this chapter is divided into five parts: Local Thermal Equilibrium (LTE) model; non-dimensionalization; special treatment for diffusion coefficient; Local Thermal Non-Equilibrium (LTNE) model and anisotropic conditions in the properties of porous media along with the LTNE model. Except for the part four, each section provides the corresponding governing equations for fluid flow inside porous media, comprising conservation of mass, momentum, energy and mixture properties in the two-phase zone along with boundary conditions. In the beginning of the first part, the derivativion of the TPMM of Wang and co-worker along with LTE model is briefly described and the physical meaning of the mixture properties in the two-phase flow is explained. Also newly proposed modification of the enthalpy formulation, termed "modified enthalpy formulation" according to the TPMM of Wang and Beckermann, is presented in detail in the first part. In the second part appropriate non-dimensionalization is provided for all the governing equations. In the third part, a special method for dealing with sharp discontinuities in the effective diffusion coefficient, which occur at the interfaces separating the single phases and the two-phase zone, is presented for the TPMM of Wang and the modified enthalpy formulation, followed by a detailed discussion. The fourth part describes the governing equations based on the TPMM of Wang along with the LTNE model. Finally, the governing equations considering anisotropy in both the mechanical and thermal properties of porous media based on the TPMM of Wang along with the LTNE model are presented in detail.

2.1. Local Thermal Equilibrium Model

As already mentioned in chapter 1, the TPMM introduced by Wang and Beckermann; Wang et al and Wang are based on the assumption of the LTE. In the LTE model, it is assumed that the temperature difference between the solid and the fluid phases can be neglected. Additionally, Darcy's law is assumed valid for both the liquid and the gas phases, the radiative heat transfer inside the porous media is neglected, and surface tension of the liquid is assumed constant. The vapor is in local thermal equilibrium with the liquid and the thermodynamic Gibbs phase equilibrium relations are assumed valid in the two-phase region. Furthermore, the properties of the porous material, like