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Coupled Calculation of Heat and Mass Transfer of Porous Media Under the Effects of External Energy Sources

Yecong He*[a], Tengjin Huang[b], Min Tan[c]

[ab] Hunan Province 2011 Collaborative Innovation Center of Clean Energy and Smart Grid, Changsha University of Science and Technology, Changsha 410114, China
[c] School of Civil Engineering, Hunan Urban Construction College, Xiangtan 411101, China
hyc1006@126.com

For the use of external energy sources, this paper studies the changes in physical parameters and mutual response principle of the metallic thermal protection system of aerospace crafts under rapid aerodynamic heating in atmospheric reentry. To analyze and compare the control equations of porous media under the effects of external energy sources properly built, analog simulation is conducted on the model built using COMSOL multi-physical field processing software, taking into consideration the influence of different geometrical parameters and physical parameters of porous media on the model. The simulation shows that under the effects of external energy sources, the porous media are pushed ahead along the transmission direction of external energy in the phase change range on the macro level and the substance temperature are constantly vibrating near the phase-change critical temperature within phase-change area on the micro level. It is concluded that the research on heat transfer coupling of porous medium is of great guiding significance for the transmission and heat transfer of micro-scale and other substances.

1. Introduction

Porous media are composite medium composed of solid or flexible skeleton and filling substances (Sheikholeslami et al., 2015). Since absolutely dense substance does not exist in a broad sense, all the substances in reality can be treated as porous media, such as rocks and soils composing lands (Fuqiang et al., 2015), biological straw, human tissue and cellular structure, food, textiles and so on, which all present characteristics of porous media on different scales (Mabood et al., 2016). Previous research focused on the effect of a single physical field with other physical fields remaining unchanged to give corresponding engineering description and scientific explanation, which resulted in large errors and even mistakes and a lack of objectivity (Rashidi et al., 2014).

In recent research, the researchers begin to consider the physical field changing and coupling in the changing porous media (Valipour et al., 2014). Descriptions and predictions closer to practical engineering application are obtained by considering the geometric deformation, stress analysis, fluid flow, heat and mass transfer, chemical reaction and phase change and other processes of porous media as well as the interaction between them (Sheremet et al., 2016, Ravi and Saini, 2016).

2. Basic parameters of the multi-space medium

2.1 Porosity

Porosity means the ratio of the total remaining volume in a porous medium excluding the solid or flexible skeleton to the total volume of the outer space occupied by the porous medium, of which the mathematical expression is formula (1):

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$$\varepsilon = \frac{\mathrm{V_{gap}}}{\mathrm{V_{empty}}} 100\% = \frac{V_P}{V_B} 100\% \tag{1}$$

Porosity can be defined in two ways according to different statistical methods (Chung and Vafai, 2014). The first porosity is the ratio of the connected pore space volume in porous media to the external volume, which is called effective porosity represented by ε_e; The second is the ratio of the non-solid skeleton space volume in porous media to the whole volume of the porous media, which is called absolute porosity represented by ε_T. Unless specially specified, the porosity in models built and research is effective porosity (Vasilyev et al., 2015).

Porosity a very important structure parameter affecting the heat and mass transfer of porous media, which is generally related to the structure, size and arrangement of the solid skeleton of porous media (Zhuang et al., 2014). In general mathematical models, a “volume average” hypothesis is adopted, which is to approximately abstract porous media to continuous media on a large scale (Kelkar et al., 2014). This hypothesis allows us to study porous media with phenomenological approach without considering specific heat and mass transfer in each pore (Bhatti et al., 2016).

2.2 Permeability

The definition of permeability originates from the Darcy Law which indicates the relationship between the fluid velocity through porous medium and the pressure gradient in that direction. Permeability is a very important transport characteristic, the value of which can be determined by the Darcy Law in formula (1):

$$u = -\frac{k}{\mu} \bullet \frac{\partial P}{\partial x} \tag{2}$$

As the mathematic form of the Darcy flow law, the Darcy formula was proposed by the French hydrology scientist Darcy in considering urban water supply in 1856. In the formula, $\partial p/\partial x$ represents the stress gradient in fluid flow, *K* the permeability, μ the dynamic viscosity of fluid and u the fluid velocity within pores. The averages of the above values are generally used on the macro level. Permeability is calculated in cm2 in physics and d (Darcy) in engineering, and the conversion relation between them is 1d=1.02x10-8 cm2.

It can be seen from the Darcy formula that there are no fixed mathematical relations between permeability and porosity, which means permeability is not a single-value function for porosity because it is also related to the distribution, size and other factors of pores (Bhatti et al., 2017; Pozzobon et al., 2014; Al-Abidi et al., 2013; Jambhekar et al., 2015). Generally, permeability can represent the size of connected pore area and pore curvature in porous media (Zhang et al., 2015; Chen and Qu, 2014). The greater the permeability is, the better the fluidity of fluid in pores is, indicating better permeability (Sasidharan, et al., 2014).

3. Phase change process of porous media under external energy sources

Phase change process of porous media under external energy sources is a typical coupled calculation problem of heat and mass transfer in unsaturated porous media. This chapter is to establish a heat and mass transfer model for unsaturated porous media on the macro level, consider mutual transformation between solid, liquid and gas phases and give proper boundary conditions and initial conditions to determine complete control equations of the model. COMSOL multi-physical field processing software is used to conduct analog analysis for the model and analyze the result and give advices.

3.1 Physical parameter setting of the porous media model

In studying heat and mass transfer of porous media phase change process under the effects of external energy sources, it is required to the influence of various gradient driving forces on coupled calculation and their complex relations. Since the physical property parameter of porous media especially that of the filler substances in porous media pore space are crucial to the correctness of the model, it is necessary to make a list to specify the physical property parameter of porous media. The latent heat of vaporization and fusion of the filling water in porous media are both set to be constant, for the water pressure changes by no more than 10% in the phase change area, according to the initial calculation result and the constant temperature phase change makes the latent heat change of fusion so slight that its impact on the model can be ignored. In case the phase-change latent heat needs to be considered in great change in air pressure, then non-constant values can be set. See Figure 1 and Figure 2 for the relationship between latent heat of phase change and pressure in water and temperature in water respectively.

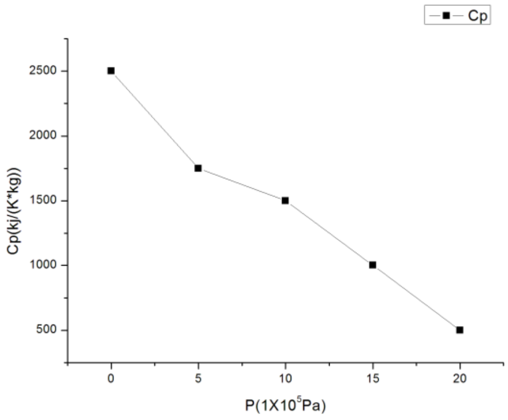

Figure 1: Relationship between latent heat of phase change and pressure in water

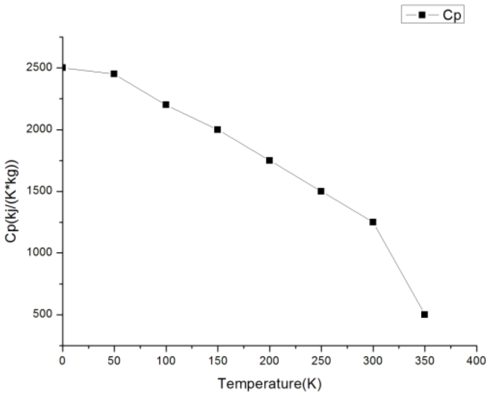

Figure 2: Relationship between latent heat of phase change and temperature in water

3.2 Two-dimensional model result and analysis

Figure 3 shows the heat and mass transfer temperature of porous media on the two-dimensional macro level:

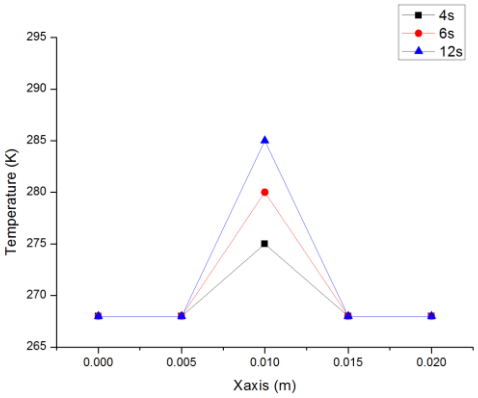

Figure 3: Changes of the boundary temperature of porous media with time

According to the figure above showing the temperature change in the central axis of the geometric model of porous media with time, the temperature rise of the porous media on the laser heating direction with continuous laser heating is much greater than that of the rest area. The temperature rises higher with time at the central axis and interface while remaining almost the same at the area around 0.0125 to form an inflection point. This is due to the heat and mass transfer of the flowing water transformed from solid in pore space in phase change process. A rough normal distribution of temperature is found at the incident interface of porous media under the effect of two-dimensional constant laser. The middle part rose higher with time and both sides almost remain the same, which is due to the existence of latent heat of phase change, making its peripheral temperature stay in the phase change area for some time and its own temperature remained around the boundary temperature of phase change.

Figure 4 shows the changes of temperature of the central axis with time in the geometric area of the two-dimensional model. It can be seen the temperature at the central axis of porous media rises gradually with time. Generally, the temperature near the wall boundary is higher than that far away from the wall boundary. As time goes on, the temperature near the wall boundary comes out of the phase-change area while that far away from the phase change remains in the phase-change area for some time. It can be seen that the temperature curve is generally descending with local vibration, which is because the temperature distribution of porous media is jointly controlled by external energy sources and internal heat and mass transfer. It can also be seen that the coupling between different physical fields in the phase change process of porous media is rather close.

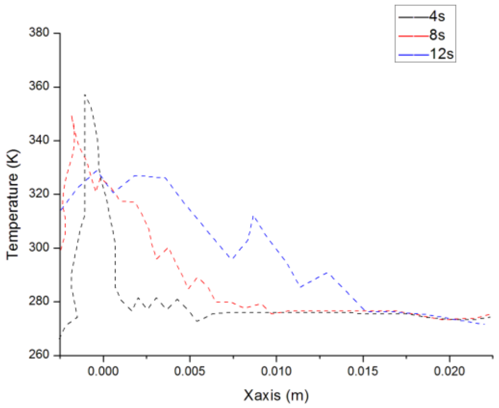

Figure 4: Changes of temperature distribution of central axis with time

According to Figure 4, the temperature at the central axis in the two-dimensional model is higher to the left and lower to the right, and this is because the external laser energy enters from the left area of the porous media, then gradually decreases along the X axis to the right and vibrates at the end of the incidence area, namely at around 0.015mm. The reason is that the phase-change liquid flows to enhance the convective heat and mass transfer intensity in the pore space, resulting in the temperature fluctuation in adjacent areas. It can be seen that the coupling between different physical fields are rather close in the phase-change process of the porous media. The coupling relationship between different physical parameters is to be analyzed and simplified in further research to obtain practical results.

3.3 Three-dimensional model result and analysis

In order to analyze the temperature change of a certain point in porous media pore space, we have obtained the temperature change curve with time at the original point of X-y plane of porous media. According to Figure 5, the initial temperature of the porous media is 263.15K, which continue to rise perpendicularly with exposure to external constant laser. The temperature of the porous media reaches 273.15K at 5s, which is the boundary temperature of porous media in phase change. The filler substance in the left pore space begins to change in phases and the temperature will not rise until the solid phase change is complete.

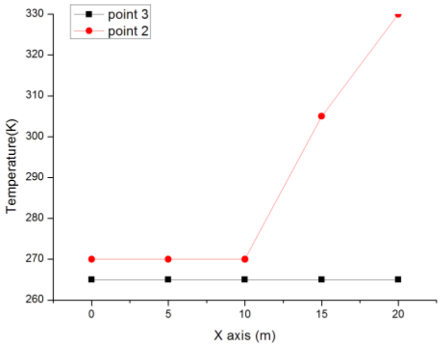

Figure 5: Variation curves of the temperature at the origin of the X-y coordinate plane with time

According to Figure 5, the temperature of the porous media at the point fluctuates within a certain range in the phase change process. This is because the phase change process of porous media is to set a minimum temperature resolution for it to absorb latent heat of phase change, during which it may be affected by other adjacent area out of the phase change temperature.

In analyzing the temperature of porous media, we may analyze the temperature distribution along the X and y axes of the X-y plane. It can be seen from Figure 6 that the temperature distribution of porous media in a plane is a rough normal distribution. At the beginning of laser heating, the distribution of the two axes varies significantly, which is because the external Gaussian laser beam is roughly and elliptically distributed resulting in uneven heating in porous media, which is more obvious at the beginning. As the heating goes on, the temperature distribution tends to be approximate distribution in parallel to the X-y plane affected by heat and mass transfer in porous media.

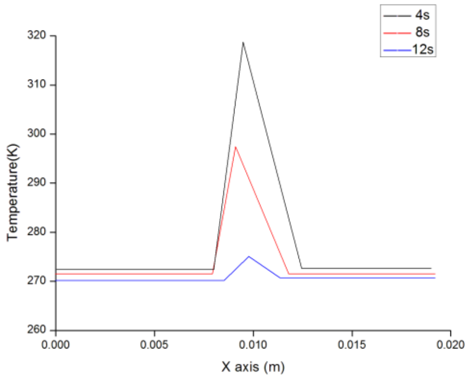

Figure 6: Variation curves of X-y axis temperature versus time in porous media

It also can be seen in Figure 6, the area near the central axis gradually comes out of the phase-change area with time, but a phase-change area between the liquid area and solid area continuously is pushed ahead with time.

4. Conclusion

This study conducts numerical simulation for the heat and mass transfer process of porous media under the effects of external energy sources in phase change. Analog simulation is conducted for the macro model established under effects of different external energy sources with the result analyzed and compared. By analyzing the influence of corresponding physical parameters on the heat and mass transfer process of porous media and the coupling relationship between different physical parameters, it turns out the simulation results the experiment are consistent with the expected purpose. Having explained the experiment structure, it has certain guiding significance for experimental and engineering applications.

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