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ON CHOOSING APPROPRIATE EQUATIONS FOR MATHENATICAL MODELING OF PROCESSES IN PCM-BASED ENERGY STORAGE SYSTEMS FOR VEHICLES

With regards to storing thermal energy, latent heat storage are the matter of growing attention over the past years due to their straightforward design, affordable production and maintenance costs, as well as universal applicability. The phase-change materials (PCM) are well-known for their widespread use in aforementioned systems primarily because of their high thermal storage density. Many studies concerning analysing and optimising the design of latent heat storage systems (LHHS) have been carried out in the last years. In relatively recent researches, different research teams have investigated different types of LHHS, using mathematical models of different levels of complexity.

The wide variety of different approaches to the mathematical modeling (including different methods, algorithms and applications from different field of pure and applied research) sometimes make it challenging to choose and implement a proper system of equations and criteria without excessive complicacies.

This very paper describes and elaborates on the system of equations that can and will be applied to the mathematical modeling of charging/recharging process in PCM-based LHHS for commercial vehicles. After a brief review of previous models, author presents the model and asses its accuracy and possibilities for further development and exploration.

Keywords: phase-change materials, mathematical modeling, latent heat, energy storage systems, thermal efficiency, non-stationery heat conduction, computational stability.

Introduction

Latent heat storage is appealing as it provides a high energy storage density and latent heat storage capacity at a constant temperature matching the phase transition temperature of PCM. Some of the most important criteria for choosing PCM are melting point, latent heat and volumetric latent heat storage capacity, since they restrict the parameters and size of the system.

The objective of this study is to develop a digital heat transfer model for predicting thermal performance of a PCM-based LHTES (latent heat thermal energy storage system) and to better understand the thermal behavior of the PCM.

A large number of publications on PCM research describing modeling and/or experiments are available in the current literature.

Analysis of the models is quite important in the development of a proper understanding of thermodynamics behavior of PCM-based energy storage systems as it takes into account lost heat and temperature in storage applications [1]. A properly performed analysis results in optimal functioning of the thermal system. The study of the problems of heat transfer in fusion and solidification processes is particularly complex due to the fact that the solid-liquid boundary shifts depending on how fast latent heat is absorbed or lost at the aforementioned boundary [2].

Materials and methods

A model of polyproplyene PCM (mixture of sodium sulphate, sodium chloride and water) tube in annular air flow was developed by Kürklü et al [3]. The model was based on the energy balance or the concept of energy conservation. It was found that the thermal properties of the PCM tube in this study had a significant effect on heat transfer, since they had a higher thermal resistance than the PCM, due to its lower thermal conductivity. Their model suggested the possibility of removing some complex assumptions such as the change of thermal properties of the PCM with temperature and the existence of convection in the liquid phase maintaining an acceptable level of accuracy and compatibility with the experimental results. The base energy equation was used for a check volume around an inner node after dividing the tube into five volumes and twenty-five units of equal length.

Model by Hamdan et Elwerr [4] considered thermal energy storage using a PCM in the rectangular enclosure the sides of which are were insulated, with the exception of the left vertical side where heat was supplied. The enclosure contained a pure PCM (n-octadecane) which was assumed to be initially in solid phase and at an initial temperature. Later in the melting process, the experimental data diverged due to the assumption that the inclination angle φ was independent of the altitude y, and due to the assumption that the walls of the enclosure were all adiabatic, except the heated one.

In the general model for heat charging and discharging processes of various LHHS having encapsulated phase change materials developed by Zhang [5] for given conditions, the system thermal behavior is shown to depend upon dimensionless solid PCM volume $(\overline{V_p})$ of the capsule which in turn depends on Fourier number (F_O) and dimensionless capsule surface (θ_s). The Fourier number was defined by the equation (1)

$$F_o = \frac{\alpha_p t}{l_c^2} \tag{1}$$

where α_p is thermal diffusivity, $m^2 \cdot s^{-1}$;

t is time, s;

l_c is the characteristic length of a PCM capsule, m [6].

The thermal efficiency of the PCM component thus determined the thermal efficiency of the whole system. Thus, LHTES thermal performance analysis could be simplified to problem of determining of $\overline{V_p}(F_o, \theta_s)$ for a capsule for the given operating conditions. That model was not limited to a specific system or to a specific PCM.

Hed and Bellander [7] in their model of a PCM air heat exchanger introduced a fictive heat transfer coefficient. That coefficient included aspects of the geometry and the airflow in the heat exchanger as well as the material properties of the PCM. The PCM temperature and the external temperature were calculated both for rough and smooth surfaces.

Within the model designed to depict the physical system with ongoing processes the following assumptions were used:

– heat transfer is modeled irrespective of the heat source and final heat receiver;

– heat transfer is considered to occur in the ideal displacement mode;

– temperature in any grid is equal;

– inlet velocity and temperature of water are constant and its flow is laminar;

– initial temperature of the PCM is uniform, the PCM itself is in the solid phase;

– thermophysical properties of water, the tube wall and the PCM are not subject to change during the process.

The PCM has a transition temperature where it during an increase in temperature and during a decrease in temperature will solidify. During melting process, the previously solid PCM in an enclosure sinks downwards or floats upwards, depending on the gravitational force, so that buoyancy is a result of differences in solid and liquid densities.

There are two key properties that should be known to the PCM equipment designer:

– heat conductivity and its variation with the temperature $\lambda_p(T)$;

– heat capacity and its variation with the temperature $c_p(T)$. (G. Hed, 2006)

The follow thermal properties of paraffin wax (acting PCM) where used to ensure computational stability:

– melting point 324.15 K (51 °C);

– latent heat 168 $kJ \cdot kg^{-1}$;

– thermal conductivity 0.22 $W \cdot (m \cdot K)^{-1}$ [8];

– specific heat 21 $kJ \cdot (kg \cdot K)^{-1}$ [9];

– density 900 $kg \cdot m^{-3}$ [10].

Results and discussion

Energy balance equation:

$$\frac{dE}{dt} = Q_g - Q_t, \tag{2}$$

where E is the energy of the system, J;

Q_g is the heat generated in the system, W;

Q_t is the heat transferred outside the system, determined by the boundary conditions, W.

Heat release equation:

$$Q_g = mC_p \frac{dT}{dt}, \tag{3}$$

where m is the mass of the system, kg;

C_p is the specific heat capacity of the system, J · (kg · K)$^{-1}$;

dT is the change of temperature, K.

Boundary condition equations should be as follows:

$$Q_{con} = h_{con} S(T_{amb} - T), \tag{4}$$

$$Q_t = \frac{kA}{e} dT,$$

where h_{con} is the coefficient of convective heat transfer, W · (m2 · K)$^{-1}$;

S is the surface area, m^2 ;

T_{amb} is the ambient temperature, K;

T is the transition temperature of the system, K;

k is the coefficient of thermal conductivity, W · (m · K)$^{-1}$;

A is the length of the cross section, m;

e is the thickness, m.

The general equation for heat generation and removal in thermal elements is based on the first equation. Thus, the volumetric heat release in the cell non-stationary sums the reversible and irreversible heat. It is possible to try to describe the heat transfer of systems with phase change materials by adding a term to the right side of the equation, taking into account heat generation and latent heat in phase change materials:

One of the most widely used methods for solving phase transition problems is the enthalpy method. The purpose of this method is to solve the energy (temperature field) equation for the solid and liquid regions in one equation. With the introduction of the enthalpy method, the constitutive equation, expressed in terms of enthalpy, allows for an interface condition that is automatically satisfied at the solid-liquid interface, as well as the creation of a softened zone between the two phases. This implies a much simpler phase transition problem. As a consequence, the crux of this fixed-mesh method is to attempt to create a mesh to solve this softened zone.

The energy conservation during a phase transition (melting or solidification) is determined by the equation:

$$\frac{dH}{dt} = \nabla\left(k_k(\nabla T)\right), \tag{6}$$

where T is the temperature of the system, K ;

H is the total volumetric enthalpy, J · kg^{-1}.

Enthalpy is the sum of latent and apparent heats and is written by the equation:

$$H(T) = h(T) + \rho_l f(T)\lambda, \tag{7}$$

and

$$h = \int_{T_m}^{T} \rho_k c_k dT, \tag{8}$$

where λ is the latent heat of fusion, $J \cdot kg^{-1}$;

ρ is the phase density of the material with the phase transition, $kg \cdot m^{-3}$.

H depends on the temperature of the phase change material:

$$\begin{cases} H = \int_{T_m}^{T} \rho_s c_s dT, \; T < T_m \; (solid) \\ H = \rho_l f(T)\lambda, \; T = T_m \; (melting) \\ H = \int_{T_m}^{T} \rho_l c_l dT + \rho_l \lambda, \; T > T_m (liquid) \end{cases} \tag{9}$$

After solving the equations (9), we obtain:

$$\begin{cases} T_{PCM} = T_m + \dfrac{H}{\rho_{PCM} C_{PCM}}, \quad when \; 0 < H \\ T_{PCM} = T_m, \quad when \; 0 < H < \rho\lambda \\ T_{PCM} = T_m + \dfrac{H - \rho_{PCM}\lambda}{\rho_{PCM} C_{PCM}}, \quad when \; 0 > H \end{cases} \tag{10}$$

It follows from the above equations that if a phase change material liquefies, the total volumetric enthalpy is equal to the latent and sensible heat. If the phase change material is solid, the enthalpy is zero. Then we can write an alternative equation for two-dimensional heat transfer in a material with a phase transition: [12]

$$\frac{\delta h}{\delta t} = \frac{\delta}{\delta x}\left(\alpha \frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(\alpha \frac{\delta h}{\delta y}\right) - \rho_l \lambda \frac{\delta f}{\delta t}. \tag{11}$$

Conclusions

The equation of non-stationary heat conduction must be solved in both phases to estimate the temperature distribution and the position of the interface during the phase transition. Analytical solutions are limited by simple boundary conditions, while the numerical solutions available for a two-dimensional model provide detailed information not only on the temperature distribution in the radial and axial positions in a cylindrical capsule, but also on the convection flow in the melt layer. It is possible to simplify heat transfer with a phase change in a vertical cylinder using a one-dimensional model and using effective thermal conductivity, which takes into account the influence of natural convection in the melt layer.

To study the thermal behavior of the engine and thermal management systems, there are several methods, including experimental and numerical simulation. The most popular approaches for studying phase transition materials in thermal systems are computational fluid dynamics and the finite element method. These are advanced methods of mathematical and numerical modeling. In these models of the heat transfer mechanism in phase change materials, the numerical solution equations are taken directly from reference books.

Such a model could be used for similar applications as long as the required changes are made to the model.

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АВТОКӨЛІК ҮШІН ФАЗАЛЫҚ АУЫСУЫ БАР МАТЕРИАЛДАР НЕГІЗІНДЕ ЭНЕРГИЯ АККУМУЛЯТОРЛАРЫНДАҒЫ ПРОЦЕСТЕРДІ МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ ҮШІН ТЕҢДЕУЛЕРДІ ЖАСАУ МӘСЕЛЕСІ БОЙЫНША

Жылу энергиясын сақтауға келетін болсақ, жасырын жылуды сақтау олардың қарапайым дизайны, қол жетімді өндіріс және техникалық қызмет көрсету шығындары, сондай-ақ әмбебап қолдану мүмкіндігіне байланысты соңғы жылдары өсіп келе жатқан мәселе болып табылады. Фазалық ауыспалы материалдар жоғарыда аталған жүйелерде кеңінен қолданылуымен, ең алдымен, жоғары жылу сақтау тығыздығына байланысты белгілі. Соңғы жылдары жасырын жылу сақтау жүйелерінің құрылымын талдау және оңтайландыру бойынша көптеген зерттеулер жүргізілді. Салыстырмалы түрде жақында жүргізілген зерттеулерде әртүрлі зерттеу топтары әртүрлі күрделілік деңгейлерінің математикалық үлгілерін пайдалана отырып, жасырын жылу сақтау жүйелерінің әртүрлі түрлерін зерттеді.

Математикалық модельдеудің әртүрлі тәсілдерінің алуан түрлілігі (соның ішінде таза және қолданбалы зерттеулердің әртүрлі салаларындағы әртүрлі әдістер, алгоритмдер және қолданулар) кейде шамадан тыс қиындықтарсыз теңдеулер мен критерийлердің дұрыс жүйесін таңдауды және енгізуді қиындатады.

Бұл мақала коммерциялық көліктерге арналған аазалық ауыспалы материалдар негізіндегі жасырын жылу сақтау жүйелерінің жүйесінде қуаттау және асыра қуаттау процесін математикалық модельдеуге қолданылатын және қолданылатын теңдеулер жүйесін сипаттайды және әзірлейді. Алдыңғы үлгілерге қысқаша шолу жасағаннан кейін автор модельді ұсынып, оның дәлдігі мен одан әрі дамыту және барлау мүмкіндіктерін бағалайды.

Кілтті сөздер: фазалық ауыспалы материалдар, математикалық модельдеу, жасырын жылу, энергия сақтау жүйелері, жылу тиімділігі, стационарлық емес жылу өткізгіштік, есептеу тұрақтылығы.

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К ВОПРОСУ СОСТАВЛЕНИЯ УРАВНЕНИЙ ДЛЯ МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ ПРОЦЕССОВ В АККУМУЛЯТОРАХ ЭНЕРГИИ НА ОСНОВЕ МАТЕРИАЛОВ С ФАЗОВЫМ ПЕРЕХОДОМ ДЛЯ АВТОМОБИЛЕЙ

Системы аккумулирования скрытого тепла в последние годы привлекает все большее внимание из-за простоты конструкции, относительно невысоких затрат на производство и техническое обслуживание, а также универсальности применения. Материалы с фазовым переходом широко используются в вышеупомянутых системах, в первую очередь из-за их высокой плотности накопления тепла. В последние годы было проведено множество исследований, касающихся анализа и оптимизации конструкции систем хранения и аккумулирования скрытого тепла. В относительно недавних исследованиях различные группы рассматривали некоторые типы подобных систем, используя математические модели разного уровня сложности.

Большое разнообразие подходов к математическому моделированию (включая различные методы, алгоритмы и приложения из разных областей научных и прикладных исследований) иногда затрудняет выбор и реализацию правильной системы уравнений и критериев.

В статье описывается и разрабатывается система уравнений, которая может и будет применяться для математического моделирования процесса зарядки и разрядки в системе накопления скрытой теплоты на основе материала, подвергающего фазовому переходу, для коммерческих автомобилей. После краткого обзора предыдущих моделей автор представляет модель и оценивает ее точность и возможности для дальнейшего развития и исследования.

Ключевые слова: материалы с фазовым переходом, математическое моделирование, скрытая теплота, системы накопления энергии, тепловой КПД, нестационарная теплопроводность, расчетная устойчивость.

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