A MATLAB BASED MODEL FOR THE ANALYSIS OF HEAT TRANSFER CHARACTERISTICS OF A PHASE CHANGE MATERIAL

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ABSTRACT: *Thermal energy storage has immense economic prospective for solar energy application in waste heat and industrial process heat applications. One of the attractive options for thermal energy storage is latent heat energy storage, which is based on heat absorption or release when a material undergoes phase change. Such materials are called phase change materials (PCM). In this work, a model based on the two phase one-dimensional Neumann solution of phase change problem, has been developed in MATLAB to study the heat transfer characteristics of a PCM. This model has been simulated with n-octadecane as PCM, which has a melting temperature of 27.7 °C. It qualifies as a promising PCM because of its suitable thermo-physical properties and uniform melting temperature. The melt fraction and latent energy stored by the PCM have been calculated. These results have been verified by comparing with that of one-dimensional Costa model under two different scenarios i.e. with conduction only and conduction plus convection.*

***Keywords**:* Thermal energy storage; phase change material; latent energy; solar energy; heat transfer; melt fraction

1. INTRODUCTION

Thermal energy storage has immense economic potential for the application of solar energy in waste heat and industrial process heat applications. Due to issues concerning environment and shortage of energy supply, solar energy systems are gaining attention. However a thermal energy storage device is necessary in such solar energy systems, because there is always a mismatch between energy supply and demand periods due to the intermittent nature of solar energy. Consequently thermal energy storage provides a valuable solution to counter this mismatch [1]. In addition, thermal energy storage can increase the overall efficiency in waste heat recovery systems, where the waste heat supply and demand periods are different.

An attractive choice for thermal energy storage is latent heat energy storage, which is based on heat absorption or release when a material undergoes a phase change [2]. Such materials offer the advantage of greater energy density per unit mass and per unit volume in comparison with conventional materials, as they have high latent heat of fusion. They store thermal energy from the heat source as they melt and release this energy for utilization as they freeze. This transition from solid to liquid and vice versa is termed as phase change and hence these materials are called phase change materials (PCM) [3]. Some of the common PCM used in solar heating systems are Glauber's salt (sodium sulphate deca-hydrate), calcium chloride hexa-hydrate and paraffin wax [4]. The feasibility of employing a PCM for energy storage depends on suitable economics, thermo-physical, kinetic, and chemical properties [5].

2. WORKING PRINCIPLE

A MATLAB model [6] based on one-dimensional (1D) two-phase Neumann solution of classical Stefan problem [7] has been developed to study the heat transfer characteristics of a PCM. The results obtained from the MATLAB model have been compared with that given by one-dimensional Costa model [8] to verify the validity of MATLAB model.

2.1 MATLAB Model

A solid semi-infinite slab is melted by imposing a uniform temperature at the left face. The right face at is kept insulated and a sharp solid-liquid interface is assumed. Solid-liquid interface is the phase transition region where the solid and liquid phases coexist. It is also assumed that thermo-physical parameters for each phase are constant. It is essential to assume that the slab is semi-infinite for this problem to be explicitly solvable as shown in Fig. 1 [7]. This semi-infinite case is a realistic approximation to the finite case because of the slow heat conduction and phase change process found in most melting and freezing processes. The physical realization of the system is an insulated pipe filled with PCM and exposed at left end to a heat source, while its length is so great that the right end is not reached within the lifetime of experiment.

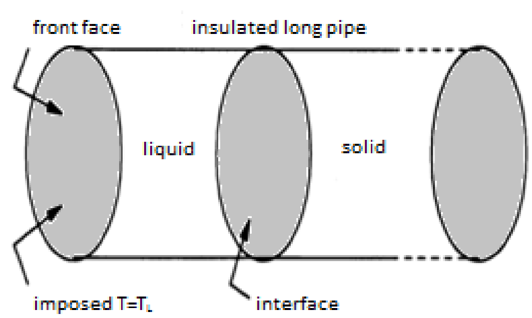

Fig. 1 Physical realization of two phase Stefan problem

2.2 Costa Model

A latent heat storage system has been designed to take advantage of the off-peak electrical energy for space heating [8]. The thermal performance of such a storage system has been analyzed using an enthalpy formulation and a fully implicit finite difference method. Calculations have been made for the melt fraction and latent energy stored for conduction only and conduction plus convection modes of one-dimensional heat transfer. The system consists of seven rectangular PCM containers made up of Aluminium as shown in Fig.2 [8]. The thickness of the used container material acts as a fin and helps to boost heat transfer rate. Ten rectangular Aluminium tubes have been fixed on one side of the PCM containers, for fluid flow and to withdraw the stored heat whenever required. An electric heater has been provided on the other side of the PCM containers to melt the PCM. The whole system is kept in a well-insulated box to provide adiabatic conditions.

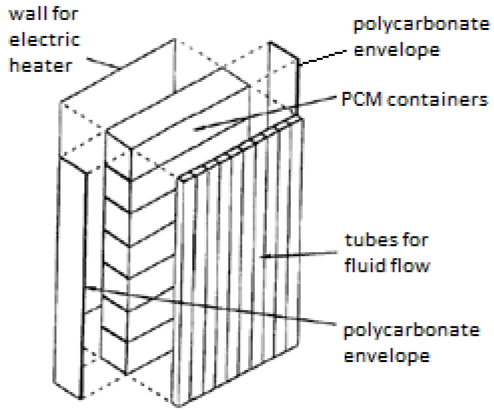

Fig. 2 Schematic of latent heat storage system

3. SIMULATION SETUP

The energy storage system employed by Costa model uses n-octadecane as PCM. It has been selected because of its relatively low and uniform melting temperature. Some of the application areas for n-octadecane are storage for domestic heating and cooling, passive storage in bio-climatic architecture, thermal storage of solar energy, application in off-peak electricity for cooling and heating and protection of electrical devices [9]. Table 1 shows the thermo-physical properties of n-octadecane [8].

TABLE I. Thermo-physical properties of n-octadecane

Melting temperature	27.7 °C
Latent heat of fusion	243.5 kJ/kg
Density (liquid)	777.0 kg/m^3
Thermal conductivity (liquid at 313 K)	0.148×10^{-3} kJ/m °C
Thermal conductivity (solid at 298 K)	0.358×10^{-3} kJ/m °C
Thermal diffusivity (liquid)	8.64 x 10^{-8} m^2/s
Thermal diffusivity (solid)	2.14 x 10^{-7} m^2/s

The heat transfer characteristics for n-octadecane are obtained by running the MATLAB model under the same conditions as that of Costa model. Initially the PCM is solid at 22.7 °C and then a temperature of 32.7°C is imposed for melting it. First of all the MATLAB model takes input in the form of thermo-physical properties of PCM: melting temperature, latent heat of fusion, density, specific heat capacities of liquid and solid phases, thermal conductivities of liquid and solid phases and system conditions: initial temperature and imposed temperature as shown in Fig. 3. Secondly it calculates the thermal diffusivities of liquid and solid phases and based on these, it calculates ν. Subsequently it calculates Stefan numbers of liquid and solid phases. After that it calculates λ. Finally the model gives the output in the form of melt fraction (the fraction of PCM that has melted) and latent energy stored.

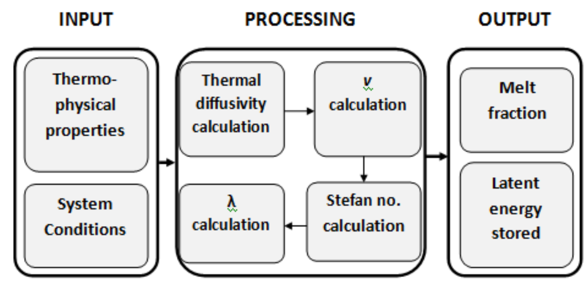

Fig. 3 Block Diagram of MATLAB Model

4. RESULTS AND DISCUSSION

The results obtained from MATLAB model have been compared with that of Costa model for verification.

4.1 Comparison between MATLAB and Costa Model with Conduction only

It has been found that the melt fraction forecasted by MATLAB and Costa Model is consistent with each other and follows the same trend as shown in Fig. 4. Up to 25 minutes the melt fraction is almost same and after some time the gap between the two curves increases, In any case the difference between the two curves is only about 5 %.

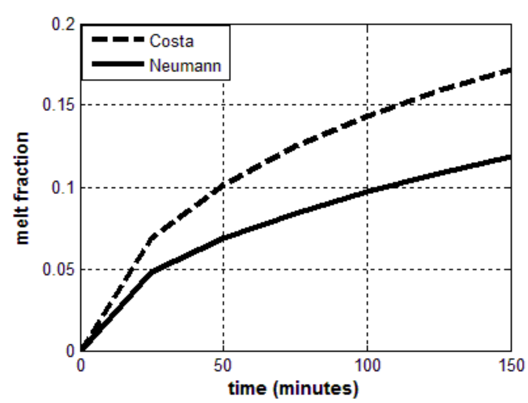

Fig.4 Melt fraction for MATLAB and Costa Model with conduction only

Fig. 5 shows that the latent energy predicted by the MATLAB model is very close to that of Costa model and it follows the same trend. Basically the energy stored by a PCM depends on its density, latent heat of fusion and solid-liquid interface location. It can be seen that after 150 minutes, latent energy stored is nearly 2200 kJ/m^2 for MATLAB model and 2000 kJ/m^2 for Costa model.

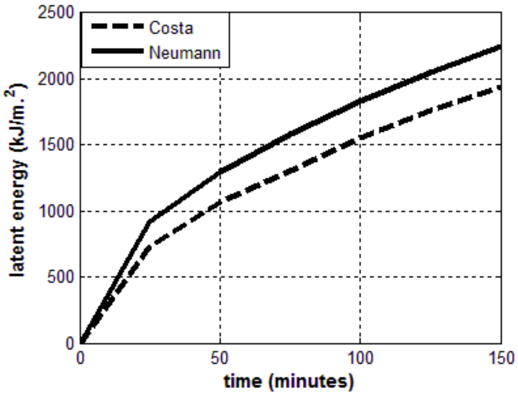

Fig.5 Latent energy stored for MATLAB and Costa Model with conduction only

4.2 Comparison between MATLAB and Costa Model with Conduction plus Convection

Fig. 6 shows that the effect of convection on the melting rate is negligible in the beginning. It can be seen that up to 25 minutes the melt fraction is almost same. However, after some time the effect of convection becomes prominent. Therefore after 150 minutes, half of the PCM has melted, if convection effect is considered while only 12% of the PCM has melted, if convection effect is not considered.

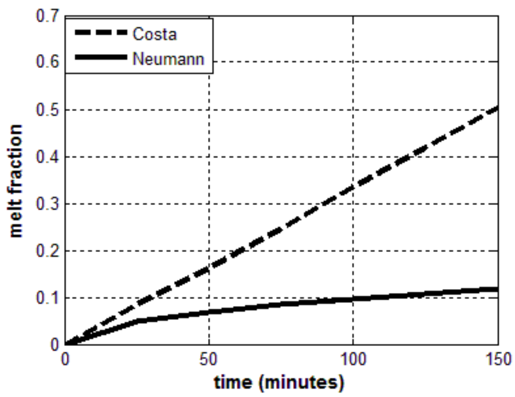

Fig.6 Melt fraction for MATLAB and Costa Model with conduction plus convection

Fig. 7 shows that in the beginning, the effect of convection on latent heat energy stored is negligible. However, after some time the effect of convection is quite prominent. It can be seen that after 150 minutes, latent energy stored is nearly 5800 kJ/m^2 if convection effect is considered while only 2200 kJ/m^2 of latent energy is stored by the system, if convection effect is not considered.

Therefore convection plays a significant role during the transfer of heat in a PCM. It has negligible effect in the beginning of the melting process as most of the PCM is in solid state. However as more of the PCM melts to liquid state, convection effect becomes dominant and melting rate of the PCM increases considerably. As a result the latent energy stored by the system, which depends on the melting rate also rises.

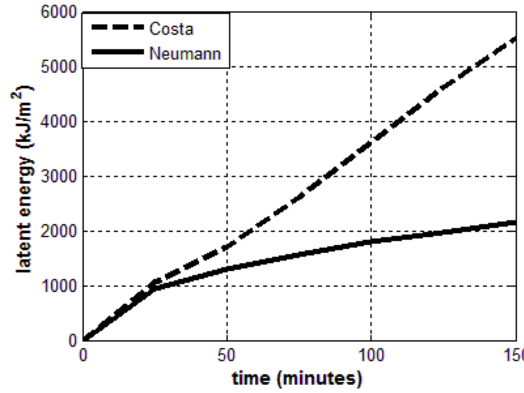

Fig.7 Latent energy stored for MATLAB and Costa Model with conduction plus convection

5. CONCLUSION

The results obtained from the MATLAB model have been verified by comparing them with that of Costa model, under two different scenarios. Firstly comparison between 1D MATLAB and 1D Costa model with conduction only shows that the melt fraction and latent energy calculated by both models are consistent with each other and follow the same trend. Secondly comparison between 1D MATLAB model and 1D Costa model with conduction plus convection demonstrates that the effect of convection is significant in calculating the melt fraction and latent energy stored. Therefore in this case a considerable difference has been found in the results given by both models.

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