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Study of Various Aspects of Phase Change Material During Solidification and Melting : A Review

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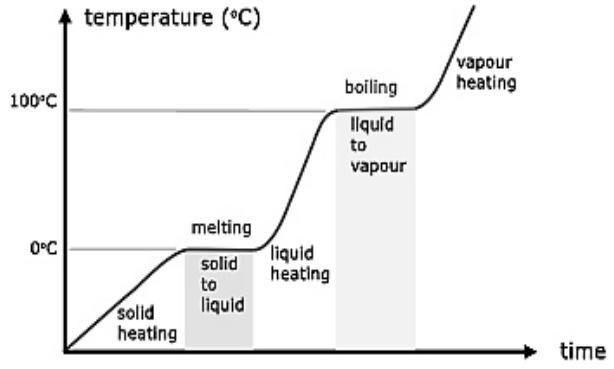
ABSTRACT

The major methods of mathematical modelling of solidification and melting problems are reviewed in this paper. Different analytical methods, nowadays still used as standard references to validate numerical models, are presented. Various mathematical formulations to numerically solve solidification and melting problems are categorized. Relative merits and disadvantages of each formulation are analyzed. Recent advances in modelling solidification and melting problems associated with convective motion of liquid phase are discussed. Based on this comprehensive survey, basic guidelines are outlined to choose a correct mathematical formulation for solving solidification and melting problems.

Keywords: Thermal Energy Storage, PCM, Latent Heat, Natural Convection.

I. INTRODUCTION

Melting is the change of state from a solid to a liquid. Melting of a pure substance occurs at a particular constant temperature called melting point. The change of state from a liquid to a solid is called **solidification** or freezing or casting. A pure substance freezes at a temperature equal to its melting point. In most of the substances, melting causes expansion and freezing causes contraction. Water is an exception. Ice melts to water causes contraction and water freezes to ice causes expansion. Density of water is highest at 4°C – water reaches minimum volume. This is why ice floats on water.



From the graph above,

- 0°C is the melting point of the solid.
- Temperature remains constant at 0°C as the solid is melting.
- During the melting process, solid and liquid exist in equilibrium.

Step by step process of what happens during melting:

1. Heat energy is absorbed by the particles
2. Heat energy is converted to kinetic energy
3. The kinetic energy of the particles increases and the particles in the solid vibrate faster
4. At melting point, the particles have gained enough energy to overcome the attractive forces between particles
5. Particles starts to move away from their fixed position
6. Liquid is formed

Cause for constant temperature during melting: The absorbed heat energy during melting is used to weaken the attractive forces between particles and not the kinetic energy of the particles.

Factors That Affect Melting Point
Melting point is affected by purity of sample and pressure on the sample.

When impurities are mixed with a pure substance, the melting point is affected. This change in the melting point has its usefulness:

- In cold countries, water in pipe lines tend to freeze in winter season, where the ambient temperature drops to below 0∘C0∘C. Freezing causes the water in the pipe to expand (recall that water expands when it freezes) and this might cause the pipe to burst. The common method to prevent this is to add antifreeze. With the addition of antifreeze, the melting point of the water + antifreeze mixture will drop to below 0∘C0∘Cand hopefully, below the ambient temperature.
- Adding salt to water can reduce its melting point to as low as -18 °C. Salt is put onto the roads in cold countries during the winter season.

Mostly substance increases their melting point when a pressure is applied in their solid state.

- Normal solids such as iron, copper undergoes expansion when they melt. When pressure is applied on the surface of a normal solid, the expansion is suppressed and melting is delayed. Thus, the melting point of a normal solid is raised by the application of pressure.
- Abnormal solids, like ice and bismuth, contract on melting into liquids. When pressure is applied on the surface of such a solid, the change into the liquid is assisted by the increase in pressure. Thus, the melting point of ice is lowered by the application of pressure.

Even though the examples above are metals, the change in melting point due to application of pressure occurs for non-metals as well. An example will be ice. With the addition of pressure, the melting point of ice will be lowered.

Note: Freezing point of pure water is 0 °C at standard atmospheric pressure. (Melting point of a substance must be stated together with its purity and surrounding pressure.).

II. LITERATURE REVIEW

1. In this paper, a new boundary element method is developed for solving nonlinear heat conduction problems with temperature dependent thermal conductivity. Radial integration method is used to deal with the domain integral due to the temperature dependence of the thermal conductivity, and the radial basis functions are employed to approximate the unknown appearing in the domain integral. The Newton–Raphson iteration method is applied to solve the final nonlinear system of algebraic equations. The given numerical examples have demonstrated the correctness of the developed method **[1].**

2. Experimental study was done in a thin rectangular chamber containing paraffin wax, used as the PCM and four types of nanoparticles at 1% mass fractions were added to the PCM to investigate performance of various thermo-physical parameters. All experimental results were compared with a previous study by the same authors with net PCM. From the results of this study, it can be generally concluded that the thermal performance of PCM based latent heat storage can be improved substantially using thermal conductive enhancers. But the heat transfer enhancement depends on many factors like, particle mass/volume concentration, particle material, particle size, temperature and additives. Additionally, it also depends on thermal conductivity, viscosity, specific heat of the mixture, interaction of the nanoparticles with the base fluid, imposed temperature and the nature of the convective flow and so on.

The careful selection of the nanoparticle and PCM (acting as the base fluid) combination considering the operating conditions and the intended use is extremely important. Because many factors simultaneously play crucial roles, a detail and comprehensive data is required before a final selection can be made **[2].**

3. The main achievements and conclusions concerning PCM characterization techniques are

- T-history is a suitable candidate technique to characterize larger samples of PCM, around 1000 times larger than DSC, and it is a simple setup that researchers can build in their own laboratory compared to the widest and expensive used technique, DSC.
- The review of the T-history provides tools to the researchers that want to build up a new one. It gives clues about the useful improvements that have been done since the original setup was published. These improvements should be in agreement and implemented in the new setups.

- To move towards a commercial available T-history it is important to get consensus among all researchers to suggest a common instrumental setup, data analysis and presentation of final results. A review has been provided to the scientific research community to contribute in this sense.
- Moreover, this review provides techniques and the conditions to characterize PCM and composite PCM from a morphological, structural, physic-chemical and mechanically point of view to the research community. Modified techniques and how to use the available ones to characterize both PCM and composite PCM is described **[3].**

4. Melting of a NePCM in a square cavity with different horizontal Source-Sink Positions on the vertical sidewalls is investigated numerically. The governing equations were solved on a non-uniform mesh using a pressure-based finite volume method with an enthalpy porosity technique to trace the solid-liquid interface. Four different cases are studied: in all Cases the source and sink are separately placed on two vertical sidewalls. It was found that, the Case 1 has the highest liquid fraction and the Case 4 possesses the lowest liquid fraction at the final stages of the melting process. In addition, the impacts of the nanoparticle loading are analyzed. In all the cases studied, the volumetric concentration of nanoparticles of 2% would result in the highest melting rate **[4].**

5. This project is focused on the available thermal energy storage technology with PCMs with different applications. Those technologies is very beneficial for the humans and as well as for the energy conservation. This project presents the current research in this particular field, with the main focus being on the assessment of the thermal properties of various PCMs. That project also presents the paraffin melt fraction studies of the few identified PCMs used in various applications for storage systems with different heat exchanger container materials **[5].**

6. In this study, the effect of nanoparticle on melting process inside shell and tube heat exchanger is numerically investigated. Results reveal that the increment of volume fraction of nanoparticle causes more penetration velocity of melt front. Also, by increasing the volume fraction of nanoparticle up to ϕ = 0.05, the total melting time is reduced to 14.6% and melt front penetration is increased to 146%. The present computations demonstrated that in a short time of the melting by increasing the volume fraction to ϕ = 0.05, the liquid fraction is increased to 44.2% **[6]**.

7. The modelling of PCM melting in three dimensional using the cell-cantered finite volume method of a fully implicit time scheme associated with a fixed grid, latent heat source approach is successfully performed. As the melting front should be of a one control volume thickness, this dominating restriction controls both the time interval and the grid sizes. The temperature distributions show that PCM cells heat up faster with a temperature gradient of almost a linear shape. Once a PCM cell is melted, its temperature increase will be slow. This clearly illustrates that the rate of heat transfer is predominantly controlled by the position of the melting front. In 3-dimensional numerical analysis was performed using FLUENT software. Analyze is done in different shape and configurations and find out the suitable configuration for heat storage applications **[7].**

8. **Purpose** – The purpose of this paper is to systematically and critically review the literature related to process design and modeling of fused deposition modeling (FDM) and similar extrusion-based additive manufacturing (AM) or rapid prototyping processes.

Design/methodology/approach – A systematic review of the literature focusing on process design and mathematical process modeling was carried out.

Findings – FDM and similar processes are among the most widely used rapid prototyping processes with growing application in finished part manufacturing. Key elements of the typical processes, including the material feed mechanism, liquefier and print nozzle; the build surface and environment; and approaches to part finishing are described. Approaches to estimating the motor torque and power required to achieve a desired filament feed rate are presented. Models of required heat flux, shear on the melt and pressure drop in the liquefier are reviewed. On leaving the print nozzle, die swelling and bead cooling are considered. Approaches to modeling the spread of a deposited road of material and the bonding of polymer roads to one another are also reviewed.

Originality/value – To date, no other systematic review of process design and modeling research

related to melt extrusion AM has been published. Understanding and improving process models will be key to improving system process controls, as well as enabling the development of advanced engineering material feedstocks for FDM processes **[8]**.

9. It was found that the shape of the cylinder greatly impacts the solidification process. This was determined by examining the Grashof Number and Aspect Ratio (AR), both of which depend on the shape of the cylinder. It was found that low AR values contribute to longer solidification times compared to high AR values. It was found that AR values above 5 were necessary for the quickest solidification times.

During solidification, the velocity decreased dramatically regardless of the AR value. The AR value did affect the amount of decrease of velocity during the solidification process. High AR values caused slower decreases of velocities causing quicker solidification compared with low AR values. Conduction was the primary heat transfer mechanism during solidification.

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10. In this we have designed a piston and piston rings for multi cylinder petrol engine Toyota Car 86 theoretically and modeled in 3D modeling software Pro/Engineer. Present used compression ratio is 10:1. In this thesis, we are calculating temperatures developed in the multi cylinder petrol engine by varying compression ratios 14:1, 15:1, 18:1, 20:1 and 25:1 by mathematical correlations. And also we have calculated pressure developed by varying the compression ratios. We have transient thermal analysis on the piston by applying the temperatures calculated for all compression ratios using two materials Aluminum alloy 6061 and Cast Iron. We have also done dynamic analysis on the piston by applying pressures calculated. And also static analysis by applying the maximum pressure. By observing the transient thermal analysis results, using compression ratio 15:1 is better since its heat transfer rate is more due to its high thermal flux value. By observing the dynamic analysis results, the analyzed stress values are less than their respective yield stress values for both Aluminum alloy 6061 and Cast Iron for all compression ratios. But by using compression ratio 25:1 is not preferable because the stress value is very high compared with that of other compression ratios. So we can conclude that using compression ratio 20:1 is better if we consider thermal and also dynamic results. And also using Aluminum alloy 6061 for piston is better than Cast Iron due to its high thermal flux values. We have also done transient thermal analysis on the piston ring. By observing the analysis results using material Cast Iron and Compression ratio 14:1 is better **[10]**.

11. Economic feasibility of industrial chemical heat pumps can be determined after calculations according to heat pump capacity. Economical calculations were carried out and curves show the relations between investment cost and capacity of chemical heat pump, capital cost and capacity of steam boiler, ICHP capacity and net savings were obtained. It is determined that the chemical system is feasible if the waste heat capacity is higher than a certain value according to lifetime of investment. Also, net gain increases linearly with increasing waste heat capacity. In Figure 5, the upper region of the net gain zero curve shows the feasible zone and it is seen that the payback period is almost constant for the capacities higher than 1000 kW **[11]**.

12. In conclusion, we have explored the thermodynamics involved in laser irradiation of silicon by 500 fs to 100 ps laser pulses. Our combined Monte Carlo and molecular-dynamics simulations reveal thermal transitions taking place between order and disorder and among different states of aggregation on mesoscopic-length and picosecond-to-nanosecond-time scales. Upon femtosecond irradiation relatively far from the melting threshold, we observe the thermal disordering of a mechanically unstable solid

in a time of _10−12 s. Under lower superheating with picosecond pulses, rapid homogeneous nucleation of liquid in the metastable solid is followed by slower, heterogeneous melting of the crystal. In contrast, solidification of the nonablated, supercooled melt to a crystal or a glass is a relatively slow process occurring on a 10−11–10−9 s time scale, independent of the pulse duration. At fluences above a well-defined threshold, hot, liquid material is ejected from the surface with a velocity of _102–103 m s−1. Under near-threshold irradiation with femtosecond pulses, the subcritical material undergoes rapid adiabatic cooling to the liquid-gas regime where a phaseexplosion- like process takes place on a 10−12–10−11 s time scale: here, the onset of ablation, determined by the growth of critical nuclei of the stable vapor phase in the metastable liquid phase, is *not* initiated by large, localized, thermal fluctuations but, rather, by a direct conversion of translational, *mechanical* energy into surface energy **[12]**.

13. The solid/liquid phase change processes in particle-laden fluids are investigated by means of experiments and numerical modeling. The effects of different particle loading percentages on the temperature histories in the domain are explored. The experimental measurements show that the slurry with lower particle loading (φ = 5%) behaves in a manner similar to melting of pure wax. Strong melt convection effects are observed in both these cases. For a heavily loaded slurry (φ = 50%), the melting process is dominated by heat conduction. A transition from convection- to conduction-dominant effects is observed in the slurry with intermediate particle loading (φ = 25%). It is also found that the diffusive flux model based on isothermal experiments is not adequate for describing the melting of slurries with different particle loadings. The model provides reasonable agreement for the dilute slurry (φ = 5%) which displays only mild particle-loading effects as well as for the very dense slurry (φ = 50%) which undergoes conduction-dominated. More advanced numerical models are needed to more accurately predict the phase change heat transfer behavior of particle-laden fluids **[13]**.

III. CONCLUSION

The merits and disadvantages of various numerical methods for phase change problems which occur in solidification and melting have been surveyed in this paper. The choice of the numerical method depends not only on the nature of the problem but also on the priorities set by the user for accuracy, computational efficiency and ease of programming. For pure substances, the variable grid methods often yield more accurate results than those based on the fixed grid method. However, the fixed grid method is very much easier to program. Moreover, the fixed grid method incorporated with the enthalpy technique can easily be extended to multidimensional problems for both pure and binary materials. Due to the importance of convection in a large number of phase change problems, wide experience has been accumulated in the numerical simulation of convection/diffusion processes coupled with phase change. Numerical techniques for such complex phenomena are now being developed by scientists and engineers in different disciplines. The popularity of the primitive variable formulation is rising since it is capable of tackling three-dimensional problems which often occur in industrial processes. On the basis of experience gained so far, numerical methods based on the weak solution in conjunction with the control volume scheme in the fixed domain can be highly recommended for multidimensional melting and solidification problems.

With increasing interest in modelling of microstructure evolution occurring during solidification, a new generation of solidification models (MT–TK) is rising. MT–TK analysis to predict various features of solidifying materials, such as dendritic structure, fraction of phases, structural transition, micro segregation and even mechanical properties. With the advent of the supercomputers, it appears that scientists and engineers are more interested in modelling of microstructure evolution occurring in solidification. The prediction of microstructure from macro transport models that solve the mass, momentum, energy and species macroscopic conservation differential equations is very limited. In order to overcome this hurdle, a new generation of solidification models which integrate the transformation kinetics (TK) into the macro transport models (MT), referred to as MT–TK models, is being

developed [1994 - 95].However, their accuracy in predicting the peculiar characteristics of microstructure is still in question.

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