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研究課題名（和文） An innovative latent thermal energy storage system encapsulated by ceramic PCM capsules for concentrated solar thermal energy plants

研究課題名（英文） An innovative latent thermal energy storage system encapsulated by ceramic PCM capsules for concentrated solar thermal energy plants

研究代表者

Ｂｅｌｌａｎ　Ｓｅｌｖａｎ (Bellan, Selvan)

新潟大学・研究推進機構・助教

研究者番号：５０７８５２９３

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研究成果の概要（和文）：球状カプセル内のPCMの相変化プロセスを研究するために、加熱炉、球状PCMカプセルおよびデータ収集システムからなる実験装置を構築した。球状PCMカプセルを電気加熱炉で加熱し、熱電対およびデータ収集システムを用いて、カプセルの中心温度を観察した。このようにして、PCMカプセルの完全溶融挙動を実験的に調べ、球形カプセルの溶融プロセスをシミュレートする数値モデルを開発した。

研究成果の概要（英文）：An experimental set up, consists of electrical heating furnace, PCM capsule and data acquisition system, has been built to study the phase-change process of the PCM encapsulated capsule. Since a large amount of heat transfer surface area can be obtained in a small volume, a packed bed thermal storage system filled with spherical PCM capsules has been considered as one of the effective methods. Hence, a spherical capsule has been made for packed bed system. PCM material was condensed in a spherical shape ceramic container. The PCM capsule was placed at the center of the heating furnace, and the temperature of the furnace was set more than 20℃ of the meting point of the PCM. The temperature at the center of the capsule was monitored using the thermocouples and data acquisition system. Thus, the complete melting behavior of the PCM capsule was investigated experimentally. A numerical model has been developed to simulate the melting process of the spherical capsule.

研究分野： thermal energy storage systems

キーワード： thermal energy storage　phase change material　latent heat storage　solar energy　concentrated solar power

１．研究開始当初の背景

International Energy Agency recently reported that global energy demand will increase by one third from 2011 to 2035, and the energy related CO_2 emission will increase by 20% if the fossil fuels are used as usual [1]. Producing electricity using concentrated solar power (CSP) is one of the promising ways for substituting conventional power generation technologies as the conventional fossil fuels are environmentally hostile and deficient due to global energy demand. However, one of the obstacles of this technology is the mismatching the supply of energy demand due to intermittent characteristics of solar radiation. Thermal energy storage (TES) system plays a vital role in CSP plant to avoid discontinues energy supply problems [2]. During daylight hours and sunny days, the thermal energy obtained from concentrated sunlight is stored in TES system; and the stored energy can be retrieved during the night hours and cloudy days. A number of research and development (R&D) activities have been performed in recent years to, improve the performance and efficiency and, reduce the construction cost of TES systems [2-3]. Basically, thermal energy can be stored in different techniques; sensible, latent and thermo-chemical heat storage. Latent heat storage in phase change materials (PCM) is considered as most attractive method since it provides high storage density than the sensible heat storage systems. Several studies have been carried out on phase change materials over the last two decades. Phase change materials are very interesting due to their consumption of large amount of energy as latent heat at a constant phase transition temperature. Literature review indicates that majority of the experimental and numerical studies were focused on saving energy in building structures (low temperature applications) with melting temperature between 20°C and 80°C. A few studies were carried out to study the melting and solidifying process of PCM capsules at high temperature, especially for concentrating solar power (CSP) applications [e.g 3-4].

As the latent heat storage technique can be used to reduce the size of the storage tank and the capital costs, packed bed latent heat thermal energy storage (LHTES) tanks were designed and investigated using spherical capsules [3]. A few studies have been investigated on melting and solidification process of phase change material encapsulated capsules. Nickel, polymer and some other metals were considered as the shell of the capsule [3-4]. However, the mechanical strength of the shell of the capsule was not good due to poor tensile strength and the thickness of the shell was irregular. Preparation of PCM capsules for LHTES system is still under active research in the CSP industry to enhance the performance and reduce the cost of latent thermal energy storage systems.

２．研究の目的

The main obstacles of the LHTES system are low heat transfer rate between the PCM and heat transfer fluid (HTF) and the corrosiveness of molten salts on the PCM metallic container. So, the main purpose of this research is to develop a high conductive ceramic PCM capsule to substantially increase the heat transfer rate and prevent the corrosion on the PCM container. In addition, the main objective is to develop a numerical model and accomplish the model validation using experimental results to perform comprehensive analysis of melting behavior and heat transfer characteristics of the capsule.

３．研究の方法

(1) Experimental method

To study the phase-change process of the PCM encapsulated capsule, An experimental set up was fabricated. Fig. 1 shows the schematic of the experimental setup which consists of electrical heater, PCM capsule, camera and data acquisition system. It is well known that the performance of the TES system greatly influenced by the geometrical configurations, which includes heat transfer rate, amount of storage material, melting/solidification time and thermocline effect. The geometry of the TES tank is classified into different types as shown in Fig. 2. Since a large heat transfer surface area can be obtained in a given volume, packed bed thermal storage system filled with PCM capsules has been considered as one of the effective methods. Hence, In this study, spherical and cylindrical capsules have been fabricated and tested for packed bed systems.

First of all, the capsule was filled by the phase change material and placed at the center of the heating furnace. Then, the temperature of the furnace was set more than melting point of the PCM. The temperature of the capsule and the near wall temperatures were monitored using the thermocouples and data acquisition system. The melting front of the capsule was captured by a camera as a function of time. After complete melting, the capsule was kept at the same temperature, and then, the temperature of the furnace was set less than the melting point of the PCM and the solidification process was monitored. Thus, the complete melting and solidification behavior of the PCM capsule was obtained. The ceramic capsule was fabricated at KYOCERA company.

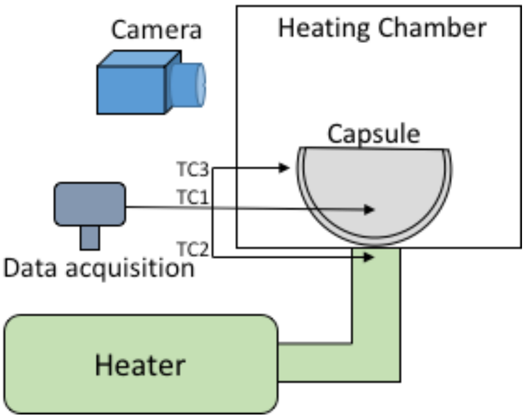

Fig. 1. Schematic of the experimental setup

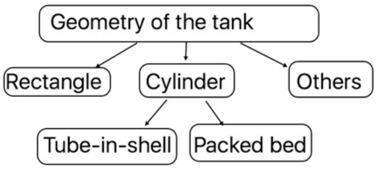

Fig. 2. Geometrical configuration of the tank

(2) Numerical analysis

An axisymmetric model has been developed by assuming the solid and liquid phases of the PCM are homogeneous and isotropic; the flow is laminar and incompressible. Based on the foregoing assumptions, the governing equations; continuity, momentum, and energy, are formulated as given below;

Continuity;

$$\partial_t(\rho) + \partial_i(\rho\, u_i) = 0$$

Momentum;

$$\partial_i(\rho u_i) + \partial_i\left(\rho\, u_i u_j\right) = \mu\, \partial_{jj} u_i - \partial_i P + \rho g_i + S_i$$

Energy;

$$\partial_t(\rho h) + \partial_i(\rho\, u_i h) = \partial_i(k \partial_i T)$$

where ρ, u, P, μ, k and T are density, velocity, pressure, dynamic viscosity, thermal conductivity, and temperature respectively. The specific enthalpy (h) is defined as the sum of the sensible enthalpy h_{sen} and enthalpy change due to phase change γL, where L is the latent heat of the material and γ is the melt fraction. The source term in the momentum equation is defined by

$$S_i = \left(\frac{C(1-\gamma)^2}{\gamma^3+\varepsilon}\right) u_i$$

where C and ε are mushy zone and computational constants respectively.

The governing equations have been solved using the finite volume method code Ansys Fluent 17. The moving PCM-Air interface of the multiphase system, without interpenetration of the two media, has been tracked by the Volume of Fluid (VOF) model. In order to solve the governing equations, the SIMPLE algorithm has been used for pressure-velocity coupling. Furthermore, PRESTO scheme has been used for pressure correction through the continuity equation. The second order upwind scheme has been employed to discretize the momentum equation.

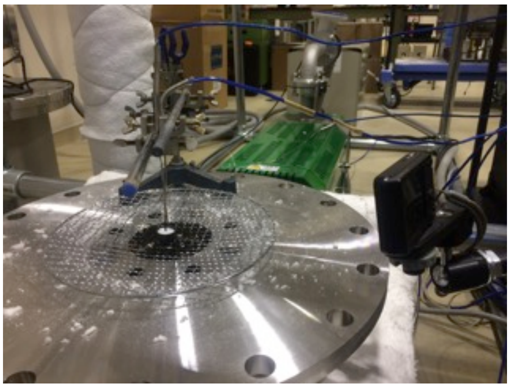

Fig. 3. Picture of the experimental setup

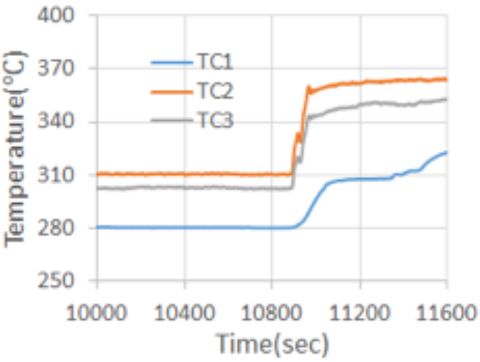

Fig.4. Time dependent temperature distributions at different locations around the capsule

The under-relaxation factors for the velocity components, pressure correction, energy and liquid fraction are 0.4, 0.3, 1 and 0.9, respectively. Convergence of the solution has been checked at each time step by the convergence criteria of 10^{-4} for the velocity components and continuity equations and at 10^{-8} for the energy equation.

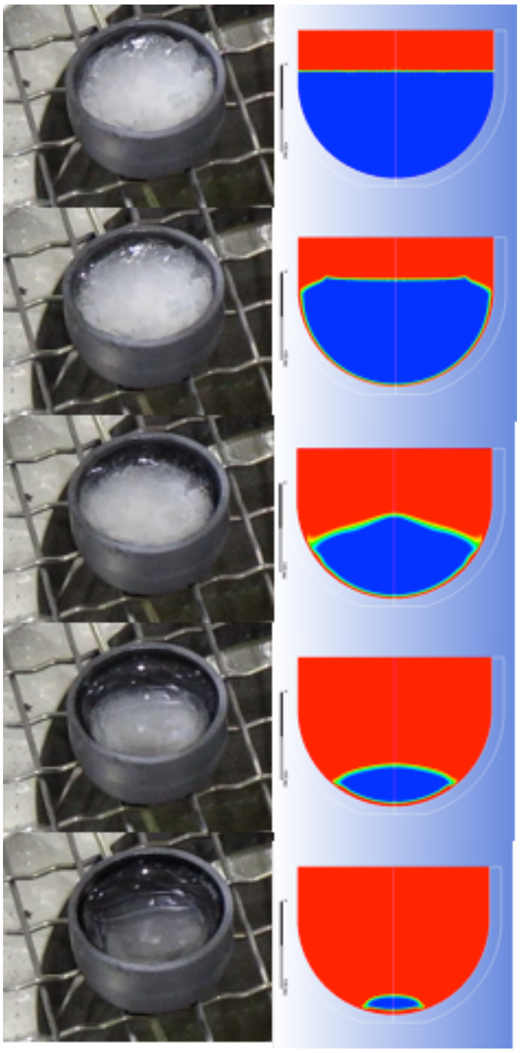

Fig. 5. Experimentally captured and numerically predicted melting front of the capsule at different instants

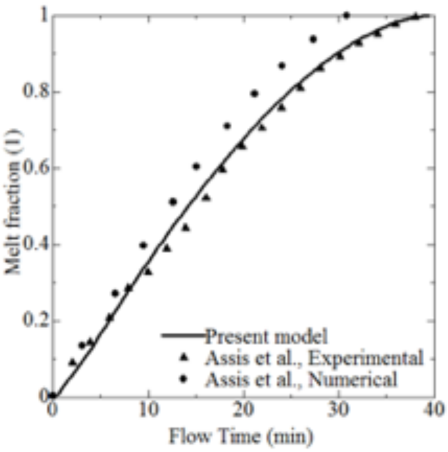

Fig. 6. Comparison of melt fraction predicted by present study and Assis et al (2007)

4．研究成果

To capture the melting front of the capsule during melting, initially, only hemisphere of the capsule was considered and sodium nitrate was filled about 65%. Then the hemispherical capsule was placed at the center of the heating chamber as shown in Fig. 3. The capsule was heated up to 280°C. after obtaining the uniform temperature, the gas flow rate and temperature were fixed at 70m³/h and 355°C respectively. The time dependent temperature distributions around the capsule were obtained as shown in Fig. 4 as a function of time. For the same operating conditions, simulations were performed. Experimentally captured and numerically predicted melting front of the capsule are compared in Fig. 5. for every 100 seconds interval. The difference between the experimentally obtained and numerically predicted melting time is about 20 seconds. As can be seen, a reasonable agreement has been found between the experimental and numerical results.

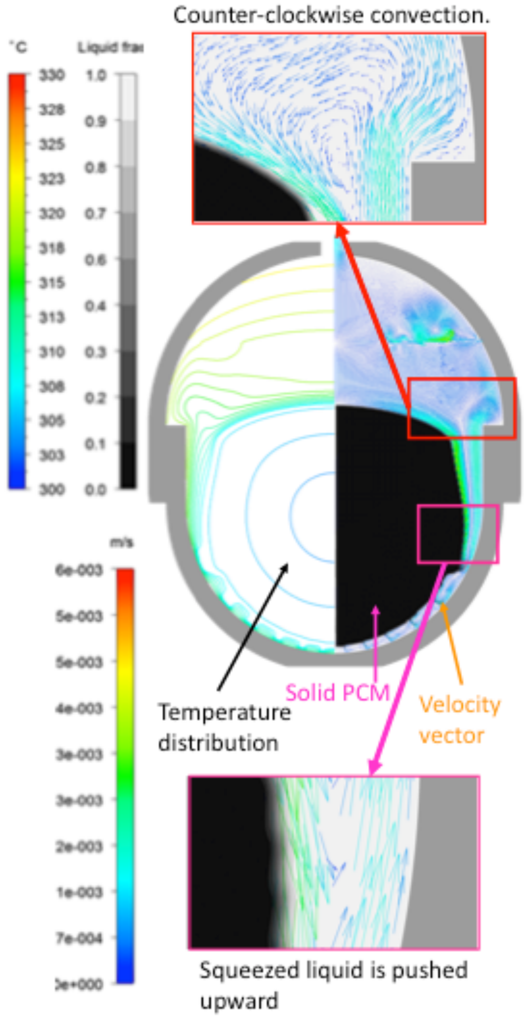

Fig. 7. Temperature distribution along with melt fraction and velocity vector at 2 minutes.

Furthermore, the developed model was applied to predict the melting behavior of the capsule of reported study of Assis et al. [5] for ΔT =10 K (Ste= 0.1). Fig. 6 shows the melt fraction as a function of time for present and previous models and experiment. It can be observed that the present study shows good agreement with the reported model [5].

Table 1. Operating parameters

Case	T_{init} (°C)	T_{HTF} (°C)	Inner radius (R_1)mm	Ste	Gr
1	300	330	11.2	0.226	9.5×10^4
2	300	320	11.2	0.130	5.4×10^4

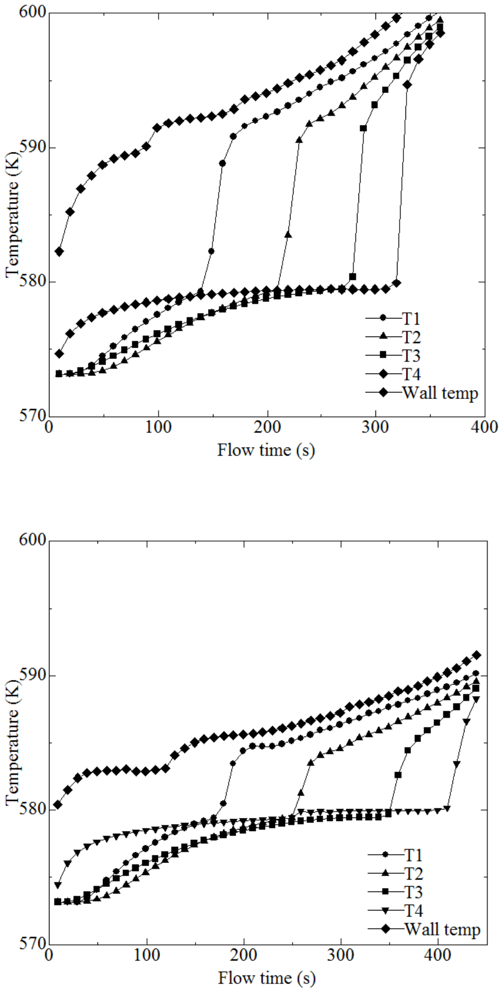

Fig. 8. Instantaneous temperature distribution of the capsule at various locations inside the capsule for case 1(top) and case 2 (Bottom)

Using the validated model, simulations were performed for couple of cases as shown in Table 1. Initially, the capsule was subcooled to 300°C. Fig. 7 shows the temperature distribution along with melt fraction and velocity vector during melting at 2 minutes. It is noticed that, during melting, the solid PCM sinks to the bottom of the capsule due to gravity force. Consequently, the solid PCM is in contact with the bottom hot surface. However, it is not a perfect contact, a thin layer is observed between the inner wall and solid PCM. During the starting stage, the heat conduction process dominates as the inner surface of the shell is in contact with the solid PCM. As time progresses, the molten zone increases between the inner wall and solid PCM, consequently the liquid layer formed at the bottom of the capsule is squeezed down by the sinking solid PCM. Thus, the squeezed liquid is pushed upward along the inner surface of the shell. Thus, the Buoyancy driven convection dominates in the side and top part of the capsule. Consequently, the rate of melting in the top region is much faster than the bottom region. Fig. 8 shows the Instantaneous temperature distribution of the capsule at various locations inside the capsule. The locations T1, T2, T3 and T3 are at the axis for every 3 mm interval from the bottom. Similarly, the melting dynamics of sodium chloride inside a cylindrical capsule was studied [6].

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５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

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６．研究組織

(1)研究代表者
Bellan Selvan（Bellan Selvan）
新潟大学・研究推進機構・助教
研究者番号：50785293