Fundamental Flow Characteristics in a Small Columnar Latent Heat Storage Bath

Hiroshi NOGAMI, Kosuke IKEUCHI and Kiko SATO

Ichinoseki National College of Technology, Takanashi, Hagisho, Ichinoseki 021-8511 Japan.

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Latent heat storage is one of the key technologies to utilize waste heat because this technology enables to store thermal energy in high density and for long time. This study focuses on flow characteristics in heat storage bath in form of direct contact since it has great effects on operation limit or thermal efficiency. The two-phase flow behavior of immiscible fluids was measured in a small cylindrical heat storage bath which had a nozzle at the center of the bottom and was settled in a rectangular transparent tank. A heating medium oil was fed from the nozzle to the bath half filled with a phase change material (PCM). Two series of the experiments were carried out. One was cold isothermal experiment which used water as model PCM, and the other was heat storage experiment which used sodium acetate trihydrate as the PCM. The formation behavior of the heating medium droplet changed from single droplet at nozzle outlet, single droplet from liquid column, multiple droplet from liquid column to atomization at the nozzle with increase in inflow velocity of heating medium. At the interface between the PCM and the heating medium, the heating medium droplets accumulated, coalesced, enlarged and disrupted, then the heating medium was released from the PCM layer. Furthermore the variation of flow behavior in the heat storage bath with progress in phase change of the PCM was elucidated.

KEY WORDS: latent heat; heat storage; flow characteristics; droplet formation; direct contact.

1. Introduction

Iron- and steelmaking industry as a huge consumer of fossil fuels receives strong social pressure to reduce energy consumption. Effective use of waste heat is one of the major solutions for energy saving. For further extension of opportunity to apply this technology, problems of three mismatches, namely, temperature level mismatch, spatial mismatch and mismatch in time between generation and utilizing sites of waste heat, arise. One of the solutions for these problems is latent heat storage that utilizes latent heat of melting/solidification of heat storage material.1) Latent heat storage is able to store much more energy in unit volume/mass compared to the sensible heat storage. This property make the heat loss from per unit stored energy become small, and it enables of long-time heat storage. Furthermore the latent heat storage supplies thermal energy at constant temperature level around the melting point of the heat storage material for long time.

Shell-and-tube, capsule and direct contact are typical styles of latent heat storage bath. In former two styles, solid partition wall exist between heat storage material and heating medium. Although this solid wall makes operation of the bath easy because it completely separates two materials, it leads following problems. a) Heat conduction in this partition wall works as heat transfer resistance, b) heat transfer area is fixed once the apparatus is constructed, and c) solidified layer formed at the surface of the partition wall works as the heat transfer resistance and makes rate of heat supply low. Contrarily in direct contact type heat storage bath in which heat storage material and heating medium directly contact each other, there is no heat transfer resistance of the partition wall, and heat transfer area can be controlled by the dispersion status of heating medium. Therefore high heat transfer efficiency in the direct contact latent heat storage bath is expected. In this type of the bath, however, insufficient separation of heating medium from heat storage material results in leakage of heat storage material from the bath, and inadequate flow pattern in the bath forms dead zone for the heat storage. Therefore it is important to understand flow characteristics of heating medium and heat storage material in the bath.

Various applications of heat storage bath of direct contact type have been proposed2,4) and their feasibility were evaluated5,6) and some of the proposed system have been practically used7,8) The flow in the direct contact type heat storage bath is treated as a two phase flow of immiscible fluid. The two-phase flow accompanies phase change, and it makes phenomena in the bath complex. Fundamental characteristics of heat transfer and fluid flow have been studied9,10) along with the process development. The relation between flow pattern and heat storage characteristics in the bath, however, has yet to be clarified. From such background, this study aims at describing the heat storage characteristics of latent heat storage bath of direct contact type from the microscopic view point of flow characteris-
tics of single droplets and/or droplets column. In this study flow characteristics in a small latent heat storage bath having single nozzle was measured.

2. Experiments

In major direct-contact latent heat storage bath, heat storage material which changes its phase at appropriate temperature (hereinafter the heat storage material is called PCM (Phase Change Material) in this paper) is charged in a vessel. Heating medium is supplied to this bath and flow up/downward due to the difference in density. During the heating medium passes through the PCM layer, two materials, namely PCM and heating medium exchange thermal energy. The bath stores heat as PCM melts, and releases heat as PCM solidifies. In this paper, combination of lighter heating medium and heavier PCM is selected, and their flow characteristics are measured in a small cylindrical heat storage bath with single hole nozzle at its bottom.

Figures 1 and 2 show schematic diagrams of heat storage bath and experimental apparatus. The bath is vertical cylinder of 400 mm in height and 50 mm in diameter. A circular nozzle locates at the center of the bath bottom. The certain amount of the PCM or water is first charged to the bath, and then the heating medium oil is fed from the nozzle. The droplets of the heating medium ascend in the PCM/water layer and form the heating medium layer above it. The upper part of the bath is filled with the heating medium and it flows out from the discharging port at the top of the bath. This cylindrical bath is settled in a rectangular transparent tank that is filled with the heating medium to observe the phenomena in the bath without deflection. For heat storage/release operations, the rectangular tank is doubly surrounded by transparent walls to form thermal insulation layers and to avoid heat loss from the bath.

The apparatus consists of the heat storage bath, pump, hot bath and data acquisition system. The temperature of the heating medium is maintained by the hot bath. The heating medium is supplied from the hot bath to the heat storage bath at constant flow rate by the gear pump. The piping between the heat storage bath and the gear pump is heated to keep the heating medium temperature at the bath inlet constant. The heating medium that flows out from the heat storage bath is send back to the hot bath and circulates in the system. The heating medium temperatures at the inlet and outlet of the heat storage bath, temperatures in thermal insulation layers and rectangular tank, and so on are measured using thermocouples and recorded by the data acquisition system. The phenomena in the heat storage bath like flow patterns, state of the PCM layer, and so on are videotaped and treated by image processing.

Two series of experiments were carried out. One was the cold and isothermal experiments and the other was the heat storage experiments. Former uses water as a model molten PCM, and the formation, ascent and separation behaviors of the heating medium droplets in/from model PCM were measured under room temperature condition. In the measurement, the bath is half filled with water and then the heating medium is supplied. The examined nozzle diameters are 1, 2, 3 and 6 mm. The flow rate of the heating medium is in the range from $0.97 \times 10^{-6}$ to $5.53 \times 10^{-6} \text{m}^3\text{s}^{-1}$. In the following section, the flow rates are classified into three levels. Small, medium and large flow rates indicates about $1 \times 10^{-4} \text{m}^3\text{s}^{-1}$, $2 \times 10^{-4} \text{m}^3\text{s}^{-1}$ and $5 \times 10^{-4} \text{m}^3\text{s}^{-1}$, respectively.

The heat storage experiments use sodium acetate trihydrate as the PCM. In the experiments certain amount of solid PCM is charged in the bath and the heating medium of which temperature is higher than the melting point of the sodium acetate trihydrate is fed from the nozzle. The heat transported by the heating medium is stored in the bath as latent and sensible heat of the PCM. Once the bath temperature rises and becomes stable, the low temperature heating medium is fed. The PCM releases heat as its solidification progresses. In the heat storage experiments, the flow rate of the heating medium varies with change in the state of PCM, thus the flow rate was measured every 600 s. The heat storing and releasing rates are calculated based on the inflow and outflow temperatures of heating medium and heat loss through rectangular tank. To determine these values, temperatures at heating medium inlet and outlet, inside rectangular tank, insulation layers and hot bath were continuously measured.

3. Flow Characteristics in Cold and Isothermal Bath

Flow and droplet formation behaviors in cold and isothermal bath, which uses water as model molten PCM and heating medium oil, were measured. Figure 3 shows droplet formation behavior from the nozzle of 6 mm in diameter under small flow rate condition ($1.07 \times 10^{-6} \text{m}^3\text{s}^{-1}$). In the initial period, the heating medium that flows out from the nozzle is retained at the nozzle tip by the interfacial ten-
The volume of the retained droplet increases with supply from the nozzle, and then it vertically extends. Next, the lower part of extended droplet starts to be pinched due to the buoyancy force acting on the upper part of the droplet. This pinched part is attenuated and broken, then spherical droplet detaches from the nozzle. The detached droplet deforms to elliptic form due to the interface shrinkage and drag force between water and heating medium. This droplet formation repeats almost same interval and column of the droplets forms in the water layer. The same droplet formation behavior is observed under the condition of fairly low flow rate of the small nozzle as shown in Fig. 4. After droplet detaches, the heating medium on the nozzle side is pulled toward the nozzle and its shape returns from steep cone to spherical. It is sometimes observed in 6 mm nozzle that a tip of the conical part of heating medium detaches to form small droplet in this process as shown in Fig. 5. This small droplet ascends following the main droplet.

The droplet formation behaviors from 6 and 3 mm nozzles under large flow rate condition ($5.53 \times 10^{-6}$ and $5.13 \times 10^{-6} \text{ m}^3 \text{s}^{-1}$, respectively) are shown in Fig. 6. For these conditions the droplet formation behavior is different from ones shown in Figs. 3 and 4. For this condition a liquid column forms at the nozzle exit and the droplet is forms from the head of this liquid column. The formation of a droplet from the liquid column, however, follows similar process mentioned above. The droplets have larger diameter than the nozzle diameter and are more deformed than the ones generated from the nozzle. The droplet diameter decreases with decrease in nozzle diameter. For the nozzle of 1 mm, the same droplet formation behavior is shown under the small flow rate condition.

The droplet formation behavior from 2 mm nozzle under medium flow rate ($2.67 \times 10^{-6} \text{ m}^3 \text{s}^{-1}$) condition is shown in Fig. 7(a). In this condition the liquid column forms at the nozzle exit and the droplets detach from the end of this column. In addition the multiple droplets generates from the column head and they disperse just above the liquid column in contrast the foregoing conditions generate single droplet from the liquid column. Moreover, the droplet diameters distribute wider than the previous cases. The nozzle of 1 mm in diameter shows similar behavior under small flow rate condition as shown in Fig. 7(b) ($0.97 \times 10^{-6} \text{ m}^3 \text{s}^{-1}$).

Figure 8 shows the state of heat storage bath under the condition of 1 mm of nozzle diameter and medium flow rate ($1.93 \times 10^{-6} \text{ m}^3 \text{s}^{-1}$). In this condition, fragmentation of the liquid column occurs and numerous small droplets disperse in the liquid layer in the heat storage bath. The droplet diameter in this condition distributed wider than the above
mentioned conditions. The 2 mm nozzle under large heating medium flow rate showed the same behavior of droplet formation.

Figure 9 shows the ascending behavior of droplets formed from 6 mm diameter under small flow rate condition. The droplets ascend not only central part but also the peripheral part in the bath although the nozzle is set on the center axis of the cylindrical bath. In addition some droplets cross the bath from one side to the other side with their ascent. The droplet ascending paths are unstable and vary with time. This droplet ascending behavior is common among the conditions with single droplet formation from the nozzle or liquid column.

Figure 10 shows state around interface between water and heating medium layers under 6 mm in nozzle diameter and small flow rate condition $\left(1.07 \times 10^{-6} \text{ m}^3 \text{s}^{-1}\right)$. The droplets came up through the water layer are once held at the interface. It is considered that the heating medium droplets are covered by water film thus the heating medium droplet keeps its form above the interface. The droplets that are retained around the interface coalesce with adjacent droplet or disrupt, and then released to the heating medium layer in the upper part of the bath. The number of layers of retained droplets increases with heating medium flow rate as the droplets form one or two layers in the condition shown in Fig. 10. Figure 11 shows the droplet layer under 3 mm in nozzle diameter and medium flow rate $\left(2.73 \times 10^{-6} \text{ m}^3 \text{s}^{-1}\right)$ condition. In this condition more amount of heating medium is accumulated as the form of droplet compared to the condition shown in Fig. 10. The droplets supplied from the water layer coalesce and form larger droplet. The supplied droplets push the retained droplets from the bottom of the layer. Finally the large droplets at the top of the droplet layer disrupt and the heating medium is released. The same behavior of the droplet layer is shown in the nozzles of 1 and 2 mm in diameter. For the condition of large heating medium flow rate in 1 mm nozzle, incomplete separation of the water and the heating medium occurs. In this condition some small droplets keep its form and pass through the droplet layer. Consequently a part of the model PCM (water) outflows from the heat storage bath as the water film on the surface of the heating medium droplets. The heating medium layer in the upper part of the bath suspends like the water layer in the lower part in this condition.

The flow behavior in the heat storage bath under cold and isothermal condition that uses water as model PCM is summarized as follows. In the low heating medium flow rate condition, single droplet is formed at the nozzle outlet. Liquid column is formed at the nozzle outlet and single droplet is formed from the end of the column when the heating medium flow rate is increased or nozzle diameter is decreased. The droplet diameter decreases with decrease in
the nozzle diameter in these conditions. With further increase in the heating medium velocity at the nozzle outlet, multiple droplets generate from the end of the liquid column. Finally the atomization of the heating medium occurs. Once atomization occurs, small droplets are suspended in both layers of model PCM (water) and heating medium in the bath. The droplet ascending path is unstable and varies with time. Around the interface between water and heating medium, the heating medium droplets covered with water film accumulate. The heating medium droplets reach to this layer coalesce, enlarge, disrupt and then are released to the heating medium layer. The volume of the accumulated heating medium droplets and the residence time in this layer increase with increase in flow rate and decrease in nozzle diameter. For the condition under which the atomization of the heating medium occur, incomplete separation of water and heating medium occurs and the water as model PCM outflows from the bath.

4. Heat Storage Experiments

In the heat storage experiments, the sodium acetate trihydrate is used as PCM, and the state inside the bath is measured during heat storage and release. For heat storage the heating medium of 75°C is fed to the heat storage bath to melt the PCM. When most PCM melts and the temperature of the bath becomes stable, the temperature of the heating medium is changed to 40°C for the heat release. After solidification of the PCM, the heating medium temperature is set again at 75°C. The heat storage and release processes are repeated. The variations of the heating medium temperatures at bath inlet and outlet and the heat storage rate in a cycle are shown in Fig. 12. In the heat storage period, the heat supplied by the sensible heat of high temperature heating medium is stored as the latent heat of melting, thus the outflow temperature of the heating medium is lower than the inlet temperature. After 130 min of heat storage, the heating medium temperature is changed and the heat releasing process starts. In the heat release period, the cold heating medium obtained heat from the melting PCM, and the outflow temperature of the heating medium becomes higher than that at inlet. In the heat release process, the temperature difference between the inlet heating medium temperature and the melting point of the PCM is set larger than that in the heat storage period. Therefore, the heat release rate is higher than the heat storage rate. The stored and released heats in this cycle were 54.78 and 54.27 kJ, respectively, while the theoretical value is 56.87 kJ.

Figure 13 shows the variation of the PCM state during the heat storage process. At the beginning of the heat storage, all PCM is solidified and the heating medium flows through crooked paths that are the interstice among the solidified PCM (Fig. 13(a)). These paths expand with the melting of the PCM, and then a bowl shaped pool of the molten PCM is formed in the upper part of the PCM layer (Fig. 13(b)). In this period the heating medium ascends in this pool as droplet and shows the similar separation behavior as cold experiments. Although the pool of the molten PCM expands toward the bottom with progress of heat storage, the PCM in the periphery region at the bottom is kept as solid (Fig. 13(c)). This heat storage bath has single nozzle at the center of the bottom. The sensible heat of the inflow heating medium first transfers upward then the convection of the molten PCM transmits the heat to the bottom periphery. Thus the heat transfer rate to bottom periphery is low and this zone becomes thermal dead zone.

The variation of the PCM layer in the heat release period is shown in Fig. 14. In the beginning of the heat release process the heating medium ascends in the molten PCM layer as a shape of droplet. The droplets are retained and disrupt at the interface similar to the cold experiment, but
their retention time is shorter and only a few droplets stay at the interface at the same time in this condition. When the bath temperature lowers around the melting point of the PCM, needle crystals of the PCM is formed on the surface of the heating medium droplet ascending in the PCM layer. The needle crystals are released to the top part of the molten PCM layer with the disruption of the droplets. The released crystals remelt in the early stage, then they circulate with recirculation flow of the molten PCM in the bath. The small crystals of the PCM are transferred to the lower part of the molten PCM layer and accumulate at the bottom part. Finally the molten PCM among the crystals solidifies then whole part of the PCM becomes solid. Even during this period, the supply of the heating medium continues therefore the crooked paths of the heating medium are formed in the solid PCM layer.

5. Conclusions

This study measured the flow characteristics in a small heat storage bath having single nozzle at the center of the bottom under cold isothermal and heat storage conditions.

(1) The diameter of the heating medium droplets generated at the nozzle decreases with decrease in the nozzle diameter.

(2) The formation mode of the heating medium droplet changes from a) single droplet formation from the nozzle outlet, b) single droplet formation from the liquid column, c) multiple droplets formation from the liquid column, to d) atomization at the nozzle outlet with increase in the heating medium flow rate and decrease in the nozzle diameter.

(3) At the interface between the molten PCM and heating medium layers, the heating medium droplets accumulate, coalesce, enlarge, disrupt and are separated from the molten PCM layer. Under the condition with the heating medium atomization, incomplete separation of the model PCM and the heating medium occurs and a part of the model PCM outflows from the heat storage bath accompanied by the heating medium.

(4) In the early stage of the heat storage process, the heating medium flows through crooked paths in the solidified PCM layer. Flow behavior becomes same manner as cold experiments in the late stage in which the pool of the molten PCM grows.

(5) Sodium acetate trihydrate as the PCM forms needle crystals on the surface of the cold heating medium in the heat releasing process. The small crystals are released to the molten PCM layer at the separation of the heating medium from the PCM layer. The crystals accumulate from the bottom part then the entire PCM layer solidifies.

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