

# A Novel Thermal Desalination Process Using Fluidized Bed

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A self-heat recuperative seawater desalination process using fluidized bed evaporator with high recovery ratio (defined as product water flow rate divided by feed water flow rate) was proposed to develop a highly energy efficient desalination process. In the process, the feed seawater may cause an agglomeration derived from liquid bridge force between particles, which finally leads to defluidization. Thus, the influence of seawater feed on the fluidization was examined. Fluidizing gas velocity was changed as a parameter. The experimental results showed that the fluidizing gas velocity of more than  $2.5 u_{mf}$  can prevent the agglomeration due to the liquid bridging. At the fluidizing gas velocity condition ( $u = 2.5 u_{mf}$  and  $3.0 u_{mf}$ ), small amount of agglomerations caused by solid bridge force was observed. However, these agglomerations did not strongly influence the fluidization and the seawater evaporation was maintained, which means that the fluidized bed can be used as an evaporator. Therefore, the novel thermal seawater desalination process using fluidized bed with high recovery ratio can be developed when the proper fluidizing gas velocity is selected.

## 1. Introduction

Self-heat recuperation technology based on exergy recuperative heat utilization has been proposed (Kansha et al, 2009). In the process based on self-heat recuperation technology, not only latent heat but also sensible heat was recovered without any heat addition, leading to drastic energy saving compared to conventional drying processes (Liu et al., 2014), distillation processes (Kansha et al., 2012), CO<sub>2</sub> gas separation process (Kishimoto et al., 2012) and cryogenic air separation process (Kansha et al., 2011). Recently, we applied the self-heat recuperation technology to thermal seawater desalination process. Our results showed that the energy consumption of the self-heat recuperative thermal seawater desalination process was reduced to 1/4 of conventional thermal desalination process (Multi-stage flash desalination) (Mizuno et al., 2013). We also reported that the energy consumption of the thermal desalination process based on the technology decreases with increasing the recovery ratio, which is defined as the ratio of the product water flow rate to the feed seawater flow rate (Mizuno et al., 2012). This suggests that the thermal seawater desalination process based on self-heat recuperation technology has a really large energy saving potential. However, at the high recovery ratio, scale (precipitation of salts in seawater) deposits on the heater surface. The formation of scale may deteriorate the heat transfer coefficient between the heater and the seawater. Then, to prevent the scale deposition on the heater surface, we proposed use of a fluidized bed as an evaporator in thermal desalination process.

The fluidized bed evaporator has the feature of the scale inhibiting capability because the feed slurry into the bed evaporates on the heated fluidized particles instead of the surface of the heat exchanger (Teunou et al., 2002). However, it is also known that an excessive amount of liquid feed into the bed could lead to agglomeration of fluidized particles, which finally leads to defluidization (Keairns et al., 1976). When the defluidization occurs, the seawater evaporation does not continue. Previous papers reported that the agglomeration/defluidization can be explained by the force balance between cohesion and segregation. Mikami et al. developed a numerical simulation model based on the balance for investigation of agglomeration on cohesive powder behaviour in fluidized bed (Mikami et al., 1997). Chaivatamaset et al. explained the bed defluidization in biomass combustion process by using a simple mathematical model constructed by the force balance (Chaivatamaset et al., 2013). Additionally, it was reported that a fluidizing gas velocity has a large impact on the agglomeration of particles in a process using fluidized bed such as

coating and granulation (Hemati et al., 2003), bio-fuel combustion (Lin et al., 2011) and solid waste incineration (Weigang et al., 2003).

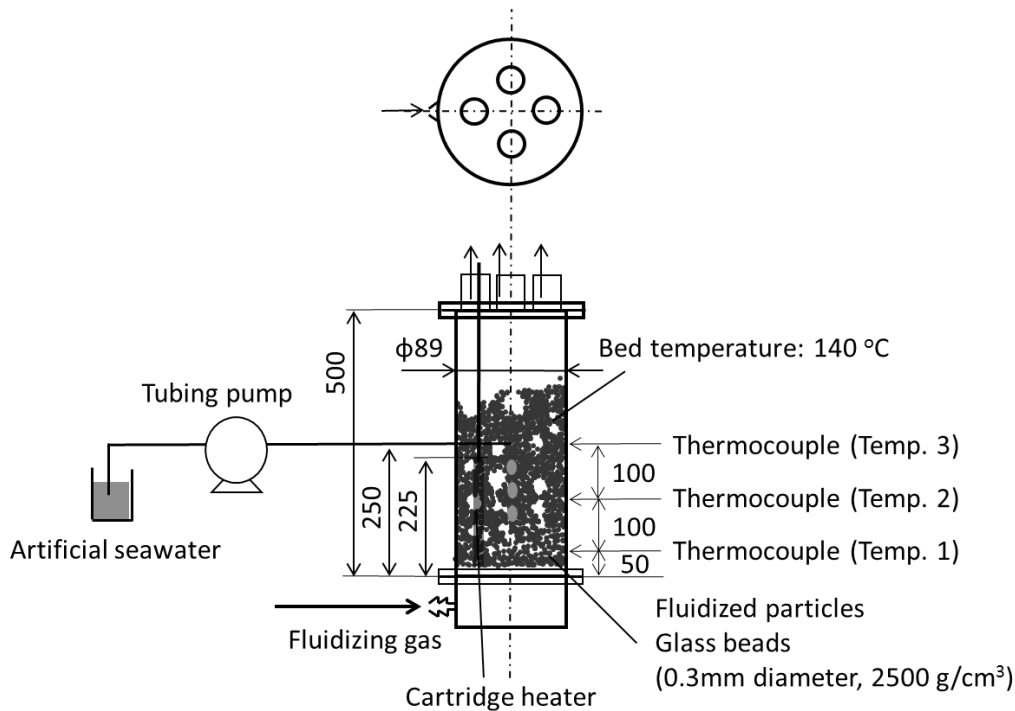


Figure 1: Experimental setup

In the present study, by using a lab-scale fluidized bed evaporator, the influence of seawater feed on the fluidization was examined. The fluidizing gas velocity was changed as a parameter. Then, the feasibility of the use of the fluidized bed as an evaporator in thermal desalination process was investigated.

## 2. Experiment

To investigate the influence of seawater feeding on fluidization, a lab scale fluidized bed evaporator was constructed and the seawater evaporation experiment was conducted. Figure 1 shows a schematic diagram of the equipment. The main body was made of glass to allow observations within the bed, and it has an inner diameter of 89 mm and a height of 500 mm. A glass filter was used as a distributor with pore sizes between 100 and 160  $\mu\text{m}$ . The fluidized particles were glass beads (0.3 mm average diameter and 2500 g/cm<sup>3</sup> density). The minimum fluidizing gas velocity ( $u_{mf}$ ) for fluidization in this bed was 9.04 cm/s. In this experiment, dry air was used as the fluidizing gas. Artificial seawater was used as the sample feed (Kester et al., 1967). Seawater was fed into the bed by a tubing pump using a 1.6 mm inner diameter silicon tube. The flow rate of seawater was 9.75 mL/min. The feed seawater was preheated by an oil bath. The pressure drop across the fluidized bed was quantified by a diaphragm-type pressure sensor that was installed before the distributor. Three thermocouples (K type) were used for the measurement of the bed temperature (Temp. 1, Temp. 2 and Temp. 3), and their locations are shown in Figure 1. The pressure drop and temperature data were logged every second. A cartridge heater made of stainless steel was immersed in the bed from the top of the equipment, and this was used to provide heat for seawater evaporation and to maintain the bed temperature at 140 °C. Its diameter and length were 16 and 200 mm. The fluidizing gas velocity was changed as a parameter ( $u = 1.5 u_{mf}, 2.0 u_{mf}, 2.5 u_{mf}, 3.0 u_{mf}$ ).

## 3. Results

Figures 2 and 3 show the pressure drop in the bed and the bed temperature for each measurement (Temp. 1, Temp. 2 and Temp. 3) with different fluidizing gas velocities of  $u = 1.5 u_{mf}$  and  $2.0 u_{mf}$ . Seawater

feed began at 300 s. From these figures, it can be seen that the pressure drop in the bed decreases with time. During the seawater evaporation experiment, large agglomerates derived from the seawater feed were

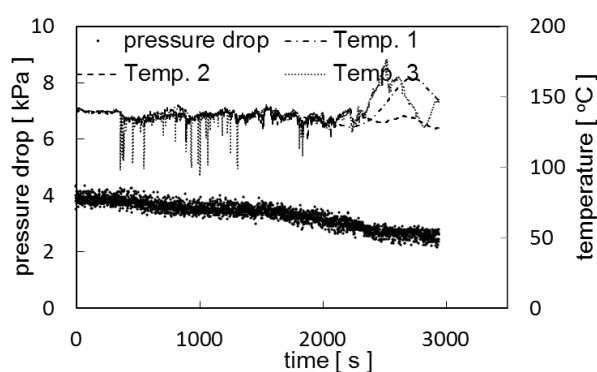


Figure 2: Pressure drop and temperature vs. time diagram at  $1.5 u_{mf}$

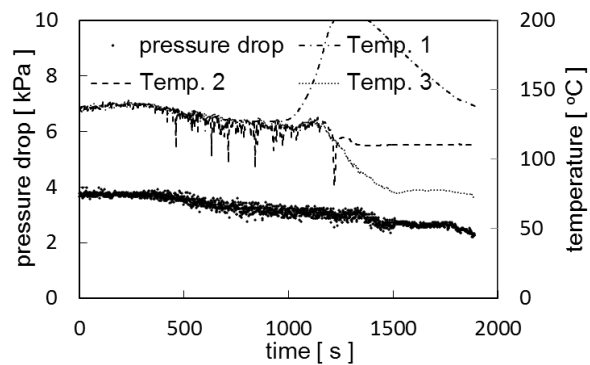


Figure 3: Pressure drop and temperature vs. time diagram at  $2.0 u_{mf}$

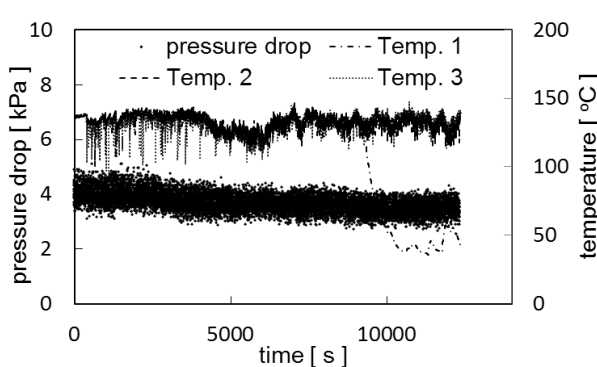


Figure 4: Pressure drop and temperature vs. time diagram at  $2.5 u_{mf}$

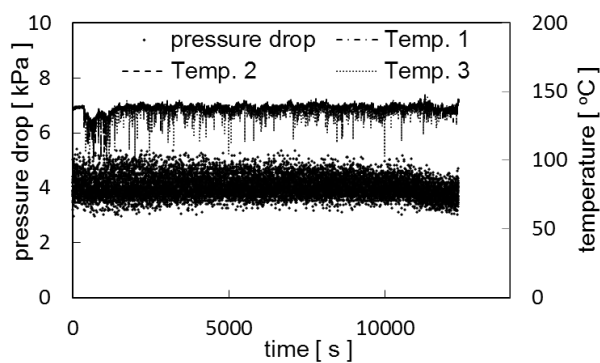


Figure 5: Pressure drop and temperature vs. time diagram at  $3.0 u_{mf}$

observed. Thus, the amount of fluidized particles decreased and this led to a reduction in the pressure drop. Furthermore, Figures 2 and 3 show that Temp. 1, Temp. 2 and Temp. 3 represent different temperatures in the bed during the seawater evaporation experiment. Usually, no temperature distribution is apparent in the fluidized bed because of good mass and heat transfer from the intensive particle motion. Hence, under these conditions, it can be concluded that defluidization took place in the bed. When defluidization occurs, seawater evaporation ceases because the heat from the heater does not transfer to the fed seawater through fluidized particles. Therefore, under fluidizing gas velocities of  $1.5 u_{mf}$  and  $2.0 u_{mf}$ , the fluidized bed cannot be used as an evaporator.

Figures 4 and 5 represent the pressure drop and bed temperature in the bed at a fluidizing gas velocities of  $u = 2.5 u_{mf}$  and  $u = 3.0 u_{mf}$ . The seawater feed began at 300 s. The amount of fed seawater was 2.0 L. While the pressure drop in the bed fluctuates because of the vigorous motion of the fluidized particles, no significant change in the average pressure drop was observed for a high fluidizing gas velocity, which indicates stable fluidization. Additionally, the Temp. 1, Temp. 2 and Temp. 3 temperatures were basically the same. Thus, under these fluidizing gas velocity conditions, fluidization was retained and seawater evaporation continued.

In Figure 4, a decrease in Temp. 1 with time after 9,000 s is apparent. This temperature reduction was caused by the accumulation of agglomerated particles on the distributor. Figure 6 shows the generation of agglomeration at  $u = 2.5 u_{mf}$  after 2.0 L seawater evaporation. The generated agglomerations can be seen at the bottom of the bed. When the height of the agglomeration region exceeded the thermocouple, contact between the sensor and the heated fluidized particles was prevented and subsequently the temperature decreased. However, as can be seen in Figure 4, the fluidization is maintained and seawater evaporation continues.

Simultaneously, the amount of scale deposition on the heater surface was investigated. The mass increase for both heaters after 2.0 L of seawater evaporation was 0.04 g for both fluidizing gas velocity

experiments, which means that the fluidized bed evaporator can prevent scale deposition on the heater surface.

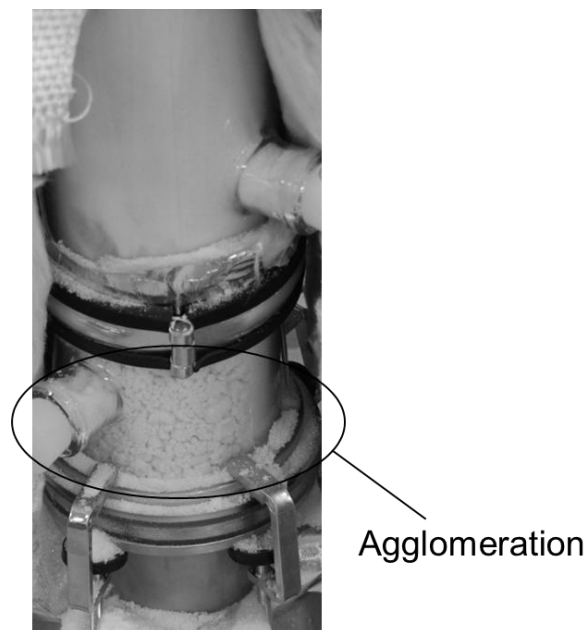


Figure 6: generation of agglomeration at  $2.5 u_{mf}$

#### 4. Discussion

The above experimental results suggest that a high fluidizing gas velocity can prevent defluidization. In previous studies, the mechanism of defluidization in combustion process such as biomass (Chaivatamaset et al., 2013) and solid waste (Weigang et al., 2003) was explained by a balance between cohesion and segregation forces. The cohesion force is mainly derived from the liquid bridge force, which is affected by parameters such as surface tension, liquid volume of the bridge, contact angle between the liquid and the solids and the curvature of the interface of the liquid bridge. The segregation force is induced by the collision force, gas bubble forces and the drag force caused by the fluid. As the fluidizing gas velocity increases, the bed mixes strongly and the segregation force increases. When the segregation force is greater than the cohesion force, agglomeration is disturbed and fluidization continues. This model can be also applied to thermal desalination process using fluidized bed evaporator because the major difference is the solvent, which mainly influences the cohesion force. Thus, the fluidizing condition in the thermal desalination process can be explained by the force balance. If a proper fluidizing gas velocity with a segregation force larger than the cohesion force is used, agglomeration due to the liquid bridge force can be prevented and the fluidized bed can be used as an evaporator in the thermal desalination process. Under these experimental conditions, the velocity was found to be  $2.5 u_{mf}$ .

Furthermore, as can be seen in Figure 6, another type of agglomeration was observed under a high fluidizing gas velocity ( $u = 2.5 u_{mf}, 3.0 u_{mf}$ ). Endo et al. reported that when water bridges including salts were vaporized, the salts crystallized to form solid bridges, which cause the agglomeration (Endo et al., 1994). They also found that the force is one to two orders of magnitude larger than the force induced by the liquid bridge without crystallization and the distribution of the cohesion force that was caused by the solid bridge force follows the Weibull distribution. Their reports agreed with the results in Figures 4 and 5, in which the segregation force was larger than the cohesion force, and agglomerations were observed. In addition, a higher fluidizing gas velocity increases the possibility of the rupture of agglomerates and a lower agglomeration formation rate because the solid bridge force follows the Weibull distribution. Thus, the amount of agglomeration caused by the solid bridge force at  $3.0 u_{mf}$  was smaller than that at  $2.5 u_{mf}$ . In the experimental results, at  $2.5 u_{mf}$  fluidizing gas velocity, the height of the agglomeration region exceeded that of the thermocouple (Temp. 1), while at  $3.0 u_{mf}$ , the height did not surpass that of the sensor, and no drop in the temperature of Temp. 1 was observed. Therefore, agglomeration can be caused by the solid salt bridge.

From the above experimental results, under the high fluidizing gas velocity condition ( $u = 2.5 u_{mf}$ ,  $3.0 u_{mf}$ ), the fluidized bed can be used as an evaporator. By collecting the generated agglomerations caused by the solid bridge force and supplying fluidized particles during the operation, the novel thermal seawater desalination process can be developed. The desalination process generates not only pure water but also salts from seawater. This means that the proposed process does not require brine disposal. Conventional desalination processes usually generate only pure water from seawater and the brine must be discarded to the environment (Cotruvo et al., 2010). Thus, the proposed use of a fluidized bed as an evaporator is also very attractive from environmental conservation point of view.

## 5. Conclusion

A novel pure water and salt coproduction process from seawater using a fluidized bed evaporator was proposed based on self-heat recuperation technology to reduce the energy consumption. Although liquid feed into the fluidized bed can cause agglomerations derived from a liquid bridge force between particles, high fluidizing gas velocity prevent the agglomeration. Under our experimental conditions, the fluidizing gas velocity of more than  $2.5 u_{mf}$  inhibits the agglomeration. At the high fluidizing gas velocity ( $u = 2.5 u_{mf}$ ,  $3.0 u_{mf}$ ), agglomerates caused by the solid bridge force were observed. The agglomerations do not strongly influence the fluidization. The stable fluidization was maintained, which means that the fluidized bed can be used as an evaporator. Therefore, when the proper fluidizing gas velocity is chosen, a novel thermal seawater desalination process, which generates salts as well as pure water with no brine disposal, can be developed.

In the proposed process, additional energy for fluidizing gas of the blower is required. For future work, influence of operating conditions, such as fluidizing gas velocity, seawater flow rate and temperature difference in heat exchanger, will be investigated in order to clarify the high energy efficient operation conditions of the proposed process. Then, the overall energy consumption will be examined and compared with conventional desalination processes.

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