Characteristics analysis of salt vacuum distillation equipment

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1. Introduction

Pyroprocessing technology was developed in the United States in the 1960s for treating metal fuels. A new technique for pyroprocessing was designed by adding an oxide reduction process to the previous one. It is regarded as a promising process to treat and recycle oxide spent fuels owing to its enhanced nuclear proliferation resistance and the simplified process equipment and the low process costing. [1-4]. Spent oxide fuel is reduced into a metal by an electrochemical method while using a high-temperature molten salt as the reaction medium. After being subjected to electrorefining and electrowinning processes, the reduced metal fuel can be used in sodium-cooled fast reactors.

The salt vacuum distillation process termed cathode processing follows the oxide reduction stage and has been developed to remove the residual salt, allowing for clear fuel metal to be supplied to the next step, which is electrorefining. KAERI has manufactured this apparatus in several sizes and has been able to achieve a fuel recovery rate of 95% [5]. However it is very difficult to scale up the equipment. Because all transport phenomena, including heat transfer and fluid flow, depend on the size and structure of the apparatus used. The ideal method for overcoming this issue is nondimensionalization, which allows one to determine the characteristic properties of a system. In this study, the structural characteristics of engineering-scale equipment were evaluated on the basis of successful data records of an M-type apparatus [5] that has been used successfully to recover molten salt in powder form.

2. Methods and Results

The advantages of using dimensionless variables are numerous: 1) a decrease in the number of variables and the number of experiments required, 2) the ability to predict the effects of changes in the individual variables by investigating the effects of varying the dimensionless parameter corresponding to the changed variable, 3) the ability to determine the correlation between the heat and fluid flows independent of the size and configuration of the system, and 4) obtaining information essential for the scaling up of the facility by simplifying the apparatus design. It is essential that the calculations be supported by experimental data and the structure size of the equipment used. The strategy to analyze dimensionless parameters consists of two approaches: 1) process characteristics of evaporation and sublimation and 2) structure characteristics of equipment.

First, the process characteristics, including the phase-transition phenomena and the exothermic and endothermic reactions involved, are studied. Salt vacuum distillation is performed at high temperatures (800–900 ℃), and the salt lithium chloride (LiCl) recovers as the powder type through evaporation and sublimation inside vacuum distillation equipment where the latent heats of evaporation and sublimation take place. Heat balance is modified by process characteristics, applying into the calculation of internal temperature and fluid flow phenomena.

Next, the structural characteristics of the apparatus used are analyzed on the basis of the dimensionless variables related to the heat and fluid flows. The representative dimensionless variables used for characterizing the heat and fluid flows using the cathode-processing apparatus are the following: the Reynolds number (Re), the Prandtl number (Pr), the Nusselt number (Nu), and the Stanton number (St).

2.1 Standard model

The first step is to define the standard model. This was taken to be a salt vacuum distillation apparatus already in use (M-type) and exhibiting efficiency of a salt recovery of more than 95% (Fig. 1). At the beginning step the evaporator is heated to the operating temperature. When the temperature of the evaporator reaches the operating temperature, the temperature of the receiver also has plateaued out at a constant temperature. The vacuum pump turns on and the inner pressure keeps 0.1-1 Torr. After the vacuum operation starts, the temperature of the receiver rises quickly due to the LiCl evaporation. The temperature begins to decrease after reaching its maximum point, at which the evaporation of the LiCl is completed. After some time, the power supplied to the heating furnace and the vacuum pump is cut off, and the apparatus is cooled down to room temperature. The condenser and the receiver are removed to recover the LiCl powder collected in the receiver, and the weight of the recovered LiCl is measured. Table 1 shows the inlet diameter and the outlet diameter of the throat wherein LiCl vapor passes through.

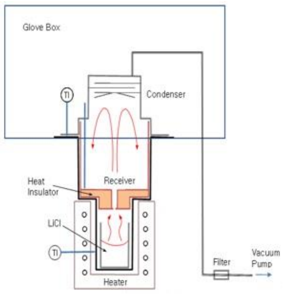

Fig. 1. Schematic figures of the salt vacuum distillation apparatus M-type [5].

Table I: Specific size of M-type throat

Inlet dia. (cm)	Outlet dia.(cm)	Length (cm)
1.7	3.4	13.6

2.2 Evaluation of dimensionless parameters of M-type

The second step is to analyze the dimensionless parameters on the basis on an analogy between heat transfer and fluid momentum. The several dimensionless parameters were calculated at the nozzle throat located between the evaporator and the receiver and at different operating temperatures. The values of these parameters were calculated at the inlet and outlet points of the nozzle throat between the evaporator and the receiver. Scale-up facilities can be technically designed by the dimensionless parameters of the standard model.
The Reynolds number (Re) for each inlet and outlet point was calculated from the corresponding velocity, as shown in Fig. 2. Here, "M" in the x-axis denotes the M-type while the numbers (800, 850, and 900) represent the operating temperatures. Finally, the letters "I" and "O" indicate inlet and outlet, respectively. In both apparatuses, the fluid flow was in the turbulence range (Re > 4000). The Re number at the outlet was higher than that of the inlet point. Because the radius of outlet is broader and as the result, the fluid velocity at the outlet point was lower. In the case of the M-type apparatus, the Re number at the outlet was 1.1 times than at the inlet.

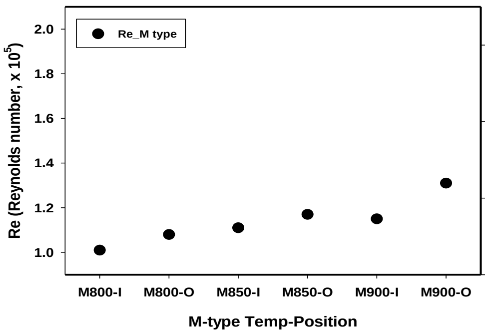

Fig. 2. Distribution of the Reynolds number.

The values of the heat-transfer factor (j_h) and the Stanton number (St) for the different positions and operating temperatures are shown in Fig. 3. There exists an analogy between various transport phenomena-related parameters, such as momentum, mass, and energy. Based on the Chilton-Colburn j-factor analogy between heat, mass, and momentum transfer heat-transfer factor (j_h) is similar to the friction factor used to describe the drop in pressure within a tube. The heat-transfer factor (j_h) values of the M-type apparatuses were 0.002–0.003 over the range of Re values (≅ 1.0 to 2.0 x 10^5) [6]. This means that the heat-transfer behavior of the nozzle was similar to that of a commercial tube. The St number for all the locations at the outlet was slightly lower than those measured at the inlet.

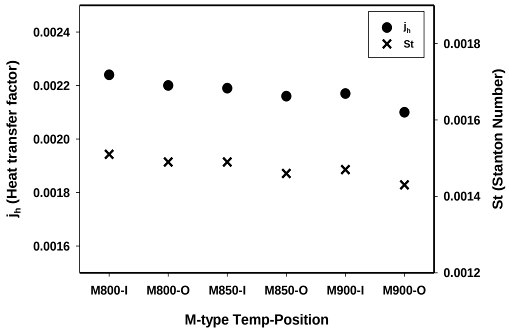

Fig. 3. Values of the heat-transfer factor (j_h) and Reynolds number for the M-type.

3. Conclusions

A new method for scaling up salt vacuum distillation based on an analysis of the dimensionless characteristics of the cathode-processing equipment was proposed. A comparison of the dimensionless variables corresponding to the M-type and P-type apparatuses performed on the basis of phase-transition phenomena as well as the results of the above-mentioned analysis elucidated the differences between the two apparatuses. It also means that the structure of the nozzle throat can be the one of the several causes for the recovery performance. First, the standard model (i.e., the M-type apparatus) was analyzed using dimensionless parameters. The characteristics of this apparatus were the following: 1) the diameter of the outlet of the nozzle throat was twice that of the inlet, 2) the ratio of the length to the diameter (L/D) was 8, and 3) the modified heat-transfer factor was 220–270. It indicates that the distribution of the modified heat-transfer factor can be the criteria of designing apparatuses regardless of their several sizes. Future studies should investigate the suitability of the approach used in this study for scaling up salt vacuum distillation under real-world conditions.

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