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Analytical solution of gravity separation model (GSM): Separation of water droplets from vapor in submerged combustion evaporator

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Abstract

As a kind of direct contact heating method, submerged combustion evaporator (SCE) has many advantages and is widely used in many engineering processes. The entrainment of water droplets in vapor significantly affects the separation efficiency of SCE with sparkling of hot gases. In order to ensure high evaporation efficiency, it is necessary to minimize water droplets containing high concentration of pollutants. Vapor separation space provides place for water droplets separating from vapor by gravity. Therefore, it is very important to study the gravity separation behavior of water droplets from vapor. Gravity separation model (GSM) for water droplets separation from vapor is elaborated in this paper, and its analytical solution for this model is described. Based on this model and its analytical solution, the effects of the gravity separation height and velocity of the vapor flow on the separation efficiency are discussed in details. It corresponds well with the existing numerical results. The results show that, all the droplets decelerate after entering the vapor flow; and it is not necessary to increase the height of gravity separation space after getting maximum separation efficiency. For the same height of gravity separation space, separation efficiency decreases with vapor velocity increasing. At constant vapor velocity, the maximum efficiency of separation for different initial velocities of droplet is the same. And the faster the initial velocity, the higher space for gravity separation is needed to get the maximum efficiency. This model could be used for the improvement of separation efficiency of SCE and optimization of its design.

Keywords: Gravity separation; Separation efficiency; Submerged combustion evaporator

1. Introduction

Submerged combustion [1,2] is a kind of heating method by direct contact of the flame or hot gases from a burner with a fluid or liquid substance such as water, oil or tar. The first record of submerged combustion evaporator is described in the British patent specification granted to Collier in 1886 (Fig. 1). This early attempt embodied nearly all the best features of the modern submerged combustion evaporator. Compared with conventional recuperative heat exchanger, the submerged combustion evaporator (SCE) has many obvious advantages [1,3,4] such as no fixed interface, direct contact, high speed and efficiency for the heat transfer. So, currently, the SCE is widely used in nuclear engineering, steel engineering [3], chemical engineering [5,6], environmental engineering [7–9] and other engineering processes, for evaporation, concentration and separation of target liquid or solution, especially for scale formation solution, for instance, with the treatment of sanitary landfill leachate [10–12].

Generally, entrainment of water droplets holding high concentration of chemical substances greatly influences the separation efficiency of evaporator and pollutes the environment. In order to ensure high evaporation separation efficiency, it is necessary to minimize water droplet content in the vapor. Vapor separation space provides place for water droplets separating from vapor by gravity. If the adequate height of vapor separation space cannot be ensured, the exhaust gas and condensate will contain much more solute, and will contaminate the environment. On the other hand, an excessive height of vapor separation space does not improve the separation efficiency significantly but increases the manufacture cost. Therefore, to define the reasonable height of the separation

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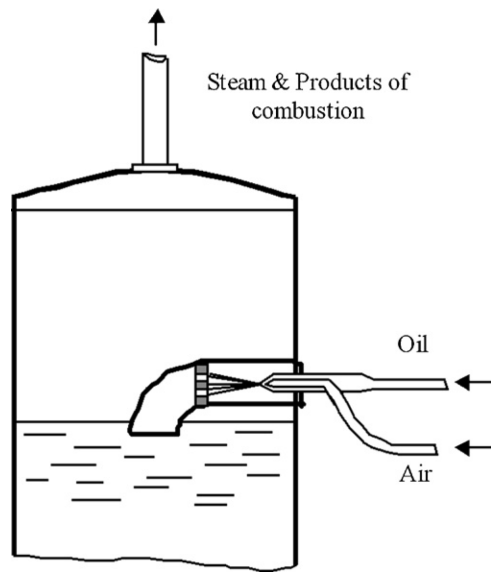

Fig. 1. The first submerged combustion evaporator.

space, it is necessary to study the movement behavior of water droplets in the vapor. However, very limited research has been conducted for investigating the phenomenon, and only numerical models were given for pressurized water reactor steam generator [13,14].

In this study, a new mathematical model is developed for gravity separation of water droplets from vapor, and an analytical solution for this model is given. Based on this model and its analytical solution, the effects of the gravity separation height as well as the velocity of the vapor flow on the gravity separation efficiency are discussed.

2. Formation and entrainment of droplets

The bubbles that consist of vapor, carbon dioxide, nitrogen, excess oxygen and some VOCs, ascend rapidly from nozzles in the liquid. When passing the liquid–gas interface, the bubble breaks down, and the broken pellicles turn into droplets. Furthermore, the collision of the surrounding liquid results in formation of larger droplets (Fig. 2). Smaller droplets formed at the interface can be carried away out of the submerged combustion evaporator. Some bigger droplets can only flow up to a certain height and then fall back down to the liquid. This height is named gravity separation height of droplet.

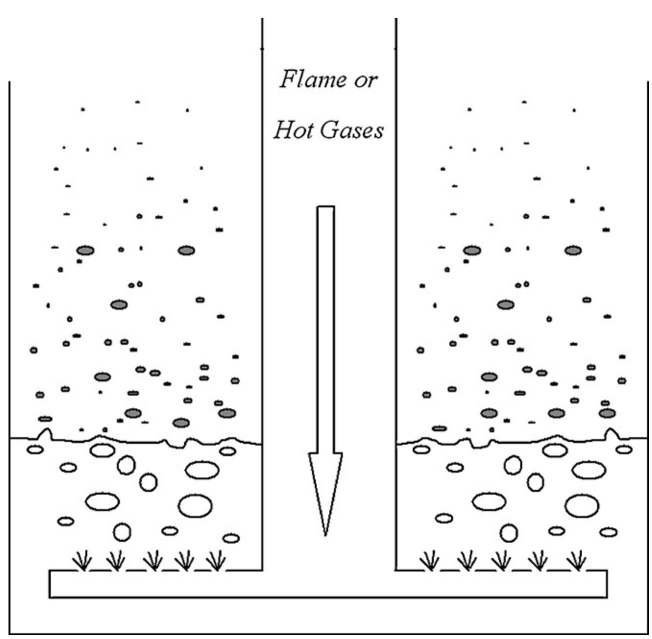

Fig. 2. Schematic diagram of formation and entrainment of droplets.