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Review

A study of the bubble column evaporator method for improved sterilization

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ABSTRACT

A bubble column was used to study sterilization using bubbles of different sizes (mm to cm) produced via bubble coalescence or by inhibiting coalescence through the addition of NaCl. The rapid transfer of heat from small, hot (dry) gas bubbles to the surrounding water was used as an effective and energy efficient method of sterilizing contaminated water. It is shown that the continuous flow of (dry) hot gases, even at 250 °C, only heat the aqueous solution in the bubble column to about 58 °C and it was also established that coliforms are not significantly affected by even long term exposure to this solution temperature. Hence, the effects observed appeared to be caused entirely by collisions between the hot gas bubbles and the coliform particles close to the sinter, where the gas bubbles were still hot enough (i.e., within 5–10 cm of the sinter surface). It was also established that the use of high air inlet temperatures can reduce the thermal energy requirement to only about 14% (about 64 kJ/L) of that required for boiling (about 450 kJ/L).

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1. Introduction

The simple bubble column evaporator presents an interesting challenge to our understanding of the detailed processes involved in bubble rise rate, water vapour evaporation and the variable effects of different solutes on bubble coalescence inhibition. Fortunately, the most important and common salt, sodium chloride, acts in solution to inhibit bubble coalescence and that behaviour has been applied to the development of a wide range of useful techniques based on the bubble column evaporator [1]. This complex system has recently been used to develop a novel method for sub-boiling, thermal sterilization [2], a thermal desalination [3] and its improvement [4] and a new method for the precise determination of enthalpies of vaporization (ΔH_{vap}) of concentrated salt solutions [5].

The thermal balance set up within a simple bubble column can be described by Eq. (1), which is based on the volumetric energy balance within the column under steady state conditions.

$$[\Delta T \times C_p(T_e)] + \Delta P = \rho_v(T_e) \times \Delta H_v(T_e) \quad (\text{in units of J/m}^3) \qquad (1)$$

ΔT is the temperature difference between the gas entering and leaving the bubble column, in units of K; C_p (T_e) is the specific heat of the gas flowing into the bubble column at constant pressure, in the units of J/m^3 K; T_e is the steady state temperature near the top of the column in the units of K; ρ_v is the vapor density at T_e, in units of mol/m^3, can be calculated from the vapor pressure of salt solutions at the steady state temperature, using the ideal gas equation; ΔP is

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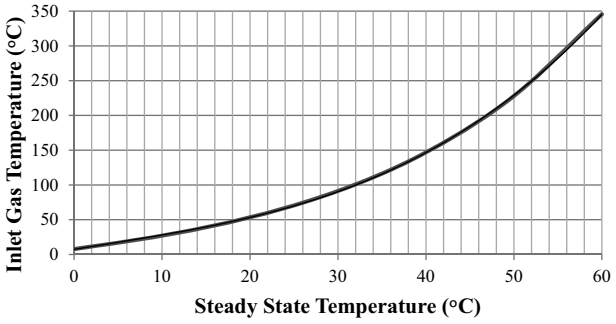

Fig. 1. Bubble column steady state temperatures calculated using Eq. (1) for nitrogen gas in pure water for a range of inlet gas temperatures.

the hydrostatic differential pressure, in units of J/m^3, between the gas inlet into the sinter and atmospheric pressure at the top of the column, which represents the work done by the gas flowing into the base of the column until it is released from the solution. Eq. (1) describes the process by which heat is supplied from warm bubbles to vaporize water from the column solution. Calculated results obtained for a water column bubbled with nitrogen gas at different inlet temperatures are given in Fig. 1. These results demonstrate the natural evaporative cooling effect produced by a bubble column.

The phenomenon of bubble coalescence inhibition was first revealed experimentally by Russian mineral flotation engineers in 1930, although this was discussed earlier by Foulk in 1929, since the addition of salt to a flotation chamber considerably improved its efficiency because finer bubbles were produced [6]. This occurs because the bubbles formed at a porous sinter, or frit, do not coalesce above a certain salt concentration. Although there is still no clear justification for this phenomenon, it has been well studied [7–10].

Only limited studies have been reported on the effects acting on indicator bacteria in large freshwater bodies, particularly at high temperatures (i.e., >60 °C). Moreover, the survival of faecal indicator bacteria (e.g., *Escherichia coli*, enterococci) in ambient environments is strongly influenced by abiotic (e.g., salinity, sunlight, and temperature) and biotic (predation and competition) factors [11].

The survival of *E. coli* populations at high temperatures depends to a high degree on the type of medium (such as milk, broth, salami, boerewors and seafoods) in which the cells were suspended. At 55 °C and 60 °C, the inactivation of *E. coli* cells (at number densities of around 10^6–10^7 CFU/mL) was recorded after 60–120 min and 15–30 min, respectively, in broth and after 180 and 30 min in milk, over this temperature range [12].

The influence of environment on three strains of *E. coli* O157:H7 (ATCC 43895, Ent C9490 and 380-94) was studied by inoculation into salami, which was then heated in water baths at 50, 55 or 60 °C. At intervals between 1 and 360 min, salami samples were removed from the water bath and examined for the presence of surviving *E. coli* O157:H7 and it was observed that the percentage of cell injury ranged from 72% to 88% for all strains. Also, strain Ent C9490 was significantly more heat resistant at 50 °C and 60 °C (*D*-values of 116.9 and 2.2 min, respectively), while at 55 °C, strain 380-94 was more thermotolerant (*D*-value of 21.9 min) [13].

Another study showed that thermal inactivation of *E. coli* O157:H7 required 60 min at 60 °C, 80 s at 65 °C and 60 s at 70 °C. This study also demonstrated that *E. coli* O157:H7 can survive in boerewors with and without preservative and is more sensitive to heat treatment at 70 °C. These results are applicable to any other fresh uncured products such as beef, pork or mutton sausages and hamburger patties [14].

In addition, thermal inactivation kinetics of individual cocktails of *E. coli* O157:H7, or of Salmonella meat isolates or seafood isolates were determined in catfish and tilapia. Studies have also demonstrated that *E. coli* O157:H7 *D*-10 values (for reduction of microbial population by 90%) ranged from 422–564, 45.2–55.5 and 3.3–4.2 s, at 55, 60 and 65 °C, respectively [15]. In summary, these various studies indicate that the coliform killing rate depends critically on both temperature and the immersion medium.

Recently, a novel approach for water sterilization was reported based on a bubble column using the bubble coalescence inhibition phenomenon to produce high bubble densities. The column contained hot bubbles ranging in sizes from 1–3 mm which rapidly transfer heat to sterilize water contaminated with biological species. This method has the potential to use a considerably lower amount of energy than the conventional method of boiling water. It is also a safer method because the water temperature of the bubble column only reaches about 45 °C even with 150 °C inlet gas temperatures [2]. The heat appears to be supplied directly to the waterborne biological contaminants, which collide with the bubbles, without heating the solution [2]. The current work was aimed at further improvements in this water sterilization process using a wider range of bubble sizes (mm to cm) and using higher inlet gas temperatures, up to 250 °C, to reduce operating times.

2. Materials and methods

2.1. Bubble column sterilization

A high surface area air/water interface was continuously created by pumping air through 40–100 μm pore size glass sinters into a 120 mm diameter, open top, glass column filled with solution to a height of about 50 mm above the sinter. The apparatus used to study sterilization using the bubble column evaporator (BCE) process with a high temperature inlet gas (air) flow is shown in Fig. 2. This system allows the use of inlet dried air at temperatures up to about 250 °C. The inlet air temperature was varied using a Tempco air heater with a thermocouple temperature monitor and an AC Variac electrical supply. The actual temperature of the dry air flowing into the solution was measured by a Tenmars thermometer (±1.5 °C), with the solution absent, just above the centre of the sinter. The air was produced using a HIBLOW air pump and was passed through a silica gel desiccator and a BOC gas flow metre. The temperature of the column solution was also continuously monitored using a thermocouple positioned at the centre of the column solution. The high temperature air flow, of up to 600 °C, needed to

Fig. 2. Photograph of the high inlet gas temperature bubble column sterilization apparatus.