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Simulation analysis on flashing process in flash chamber

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Abstract. Flash evaporation is very widely used in industrial applications. Based on the heat and mass transfer mechanism of flashing process, the equilibrium model and non-equilibrium model of flashing are established. The variation of pressure and temperature during flashing process is calculated. The results have a good agreement with the experimental data. Moreover, it can provide a guide for the industrial application of flash evaporation.

1. Introduction

When the liquid at a certain temperature is suddenly exposed to an environment below its saturation pressure, the liquid cannot store all the sensible heat. The excess heat is transformed into the latent heat of vaporization, and a lot of the vapor generate with a significant temperature drop. This phenomenon is called flashing evaporation or flashing. Compared with ordinary evaporation, the flash evaporation process has faster evaporation rate and generates large amount of steam. Therefore, it is widely used in industrial applications, such as marine steam accumulator [1], spray flashing and food processing, seawater desalination [2-4], drug drying [5], cooling of space shuttles, geothermal energy generation and ocean thermal energy conversion [6,7]. Flash evaporation not only has a beneficial application, but also adversely effects on industry production, e.g. the LOCA of the nuclear power plant [8].

Static flashing and circulating flashing of water in the pool or the pipe is widely used, e.g. seawater desalination and LOCA. Many literature has been studied the flashing model originated from the industry production. In these researches, the influence parameters such as temperature, pressure, flash mass, flash wave of the flash process were studied. Miyatake O[9,10] has explored the flashing of pool water, and proposed a dimensionless number NEF to characterizes the temperature variation of the flash process. Moreover, many experimental studies on the parameters affecting the flash phenomenon were conducted by Ji Kim[11], WX Jin[12], E. Hahne[13], D. Saury[14,15], Zhang Dan[16,17] et al. They obtained the relation between the flashing time, flash mass, flash speed and the initial temperature, initial superheat, initial water level.

In addition, the mechanism and theory model of flash phenomenon have been studied with the help of combination of computer method and experimental research. J. Bartak[18] built a model based on the LOCA to simulate the bubble behaviour of the flash process under rapid depressurization. They believed that some rebound after the rapid pressure drop is resulted from homogeneous nucleation. Based on this assumption, they acquired a modified homogeneous nucleation model. Moreover, they studied the



effects of initial temperature and pressure drop rate on the negative pressure pulse. T. Watanabe[19] also explored the mathematical model of flashing. Based on mass and energy conservation, the equilibrium model and non-equilibrium model of the flash process were established.

The experiment study is an authentic and detailed method of the process. However, limited by the actual experimental conditions, some parameters in the experiment are difficult to observe. Besides, the experimental cost and the experimental platform establishment result in difficulties to experimental research. As a supplement to the experiment, simulation has an important role in the researches. Parameters are difficult to change and study in experiments, that are easily observed and analyzed in the simulation. The simulation also has the advantage of greatly shortening the research time, improving the research quality, and reducing the research cost. Hence, the simulation of the flash process was carried out based on two different mathematical models, the equilibrium model and the non- equilibrium model, respectively.

2. Flashing Model

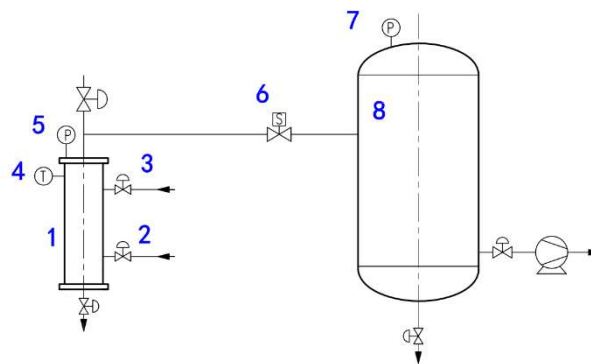


Figure 1. Flash evaporation system setup

1- Flash chamber, 2- Intake valve, 3- Water filling valve, 4- Temperature sensor, 5- Pressure transducer, 6- Electromagnetic valve, 7- Pressure gauge, 8- Vacuum tank.

2.1. Equilibrium model of flashing

This model assumes that the vapor phase is an ideal gas in the saturated state. The vapor-liquid phase state in thermodynamic equilibrium and the flashing system is a adiabatic system ignoring the volume change of the liquid phase.

The system can be divided into two subsystems, including a liquid phase subsystem and a vapor phase subsystem, in which the liquid phase subsystem is $m - dm$ at time t , the temperature is T ; at the moment $t + dt$, the mass is constant, the temperature turn into $T + dT$. For the vapor phase subsystem, the mass is dm at the moment t , the temperature is T ; at the moment $t + dt$, the mass is constant, however the temperature change into $T + dT$. In the process, this part changes from the liquid phase to the vapor phase. According to the energy conservation:

$$mc_{vl}T = (m - dm)c_{vl}(T - dT) + dm[c_{vl}(T - dT) + r] \quad (1)$$

The liquid mass in the flashing chamber at time t is:

$$m(t) = m_0 \exp \left[\frac{c_{vl}(T(t) - T_0)}{\lambda} \right] \quad (2)$$

Evaporation rate:

$$m_{er} = -\frac{dm(t)}{dt} = -\frac{m_0 c_{vl}}{r} \exp \left[\frac{c_{vl} (T(t) - T_0)}{\lambda} \right] \frac{dT(t)}{dt} \quad (3)$$

Where m_0 is initial liquid mass of flash chamber (kg), T_0 is the initial temperature of liquid ($^{\circ}\text{C}$), $T(t)$ is the temperature of liquid at time t ($^{\circ}\text{C}$), c_{vl} is specific heat of liquid at constant volume ($\text{kJ}/(\text{kg} \cdot ^{\circ}\text{C})$), λ is the latent heat of vaporization of water (kJ/kg).

Considering the vapor phase as a control volume, the mass conservation equation for the vapor phase is given by:

$$\frac{dm_g}{dt} = m_{er} - m_0 \quad (4)$$

By combining the ideal gas assumption and the Bernoulli equation, the discharge rate can be expressed as:

$$m_0 = A_0 \sqrt{2\rho_g p} \psi \left(\frac{p_b}{p} \right) \quad (5)$$

Where A_0 is flow cross-section area of flash chamber (m^2), ρ_g is vapor density (kg/m^3), p is the pressure of flash chamber (Pa), p_b is back pressure (Pa), γ is the specific heat ratio.

$$\psi \left(\frac{p_b}{p} \right) = \sqrt{\frac{\gamma}{\gamma-1}} \left[\left(\frac{p_b}{p} \right)^{2/\gamma} - \left(\frac{p_b}{p} \right)^{1+1/\gamma} \right]^{\frac{1}{2}} \quad (6)$$

The vapor phase expression is as follows:

$$m_g c_{vg} \frac{dT_g}{dt} = (m_{er} - m_0) \frac{p}{\rho_g} + m_{er} \frac{p}{\rho_l} \quad (7)$$

Where m_g is the mass of flashing chamber (kg), u_g is the specific internal energy of vapor (kJ/kg), h_g is the vapor specific enthalpy (kJ/kg), c_{vg} is the specific heat of vapor at constant volume ($\text{kJ}/(\text{kg} \cdot ^{\circ}\text{C})$), ρ_l is liquid density (kg/m^3).

The energy conservation of the liquid phase is given by:

$$m_l c_{vl} \frac{dT_l}{dt} = -m_{er} \lambda + \frac{m_l}{\rho_l} \frac{dp}{dt} \quad (8)$$

Where m_l is liquid mass (kg), u_l is the specific internal energy of liquid (kJ/kg).

2.2. Non-equilibrium model of flashing

Under the assumptions of adiabatic system with the vapor phase to be the ideal gas, and vapor-liquid phase are in thermodynamic equilibrium state. The model has been established according to the energy conservation and the mass conservation.

$$\frac{dM_l}{dt} = m_{nl} \quad (9)$$

$$\frac{dH_l}{dt} = m_{nl} h'' + V_l \frac{dp}{dt} \quad (10)$$

The vapor phase subsystem expression is as follows:

$$\frac{dH_g}{dt} = m_c h_g + m_{ng} h'' + V_g \frac{dp}{dt} \quad (11)$$

$$M_l v_l + M_g v_g = V \quad (12)$$

Evaporation rate of liquid phase [19]:

$$m_e = \frac{\rho_l V_l (h_l - h')}{\tau_e \lambda} \quad (13)$$

Where V_g , V_l , ρ_l , and h_l are vapor phase volume (m^3), liquid phase volume (m^3), liquid phase density (kg/m^3), specific enthalpy (kJ/kg), respectively.

$$v_l = v_l(p, h_l), v_g = v_g(p, h_g) \quad (14)$$

$$v_l \frac{dM_l}{dt} + v_g \frac{dM_g}{dt} + M_l \left(\left. \frac{\partial v_l}{\partial p} \right|_h \frac{dp}{dt} + \left. \frac{\partial v_l}{\partial h} \right|_p \frac{dh_l}{dt} \right) + M_g \left(\left. \frac{\partial v_g}{\partial p} \right|_h \frac{dp}{dt} + \left. \frac{\partial v_g}{\partial h} \right|_p \frac{dh_g}{dt} \right) = 0 \quad (15)$$

The formula of the depressurization rate is [20]:

$$\frac{dp}{dt} = \frac{\left(\left. h_l \frac{\partial v_l}{\partial h} \right|_p - v_l \right) \frac{dM_l}{dt} + \left(\left. h_g \frac{\partial v_g}{\partial h} \right|_p - v_g \right) \frac{dM_g}{dt} - \left. \frac{\partial v_l}{\partial h} \right|_p m_{nl} h'' - \left. \frac{\partial v_g}{\partial h} \right|_p (m_c h_g + m_{ng} h'')}{M_l v_l \left. \frac{\partial v_l}{\partial h} \right|_p + \left(\left. \frac{\partial v_g}{\partial p} \right|_h + v_g \left. \frac{\partial v_g}{\partial h} \right|_p \right) M_g} \quad (16)$$

3. Results and Discussion

Figure 2(a) shows the simulated and experimental pressure curve, respectively. It can be seen that the evolution of simulated pressure is good consistent with the experimental results. However, there is a short constant period of pressure at the beginning of experiment, which does not occur in the simulation. That is about to be a large amount of steam is generated by the intense evaporation during the flashing

process, the same emission rate results in a short-term pressure balance. This also can be obtained from the evolution of pressure in the flash chamber and the back pressure tank in Figure 2(b)[21]. The factor is ignored in the model, so the simulation results are slightly different from the experimental results.

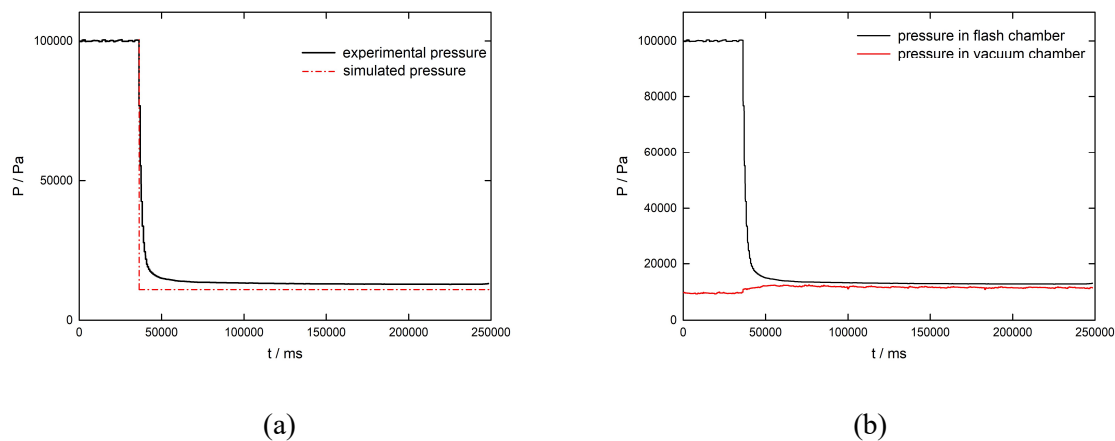


Figure 2. Pressure evolution of flashing

Figure 3 illustrates the temperature curve of the flash chamber under initial temperature of 85 °C, superheat of 10 °C, and initial water level of 450 mm. It is observed that the temperature drops rapidly and then gradually decreases. Furthermore, it indicates that the liquid rapidly vaporized from the initial instability state, and then gradually reach equilibrium state of the vapor-liquid phases with bubble generation and collapse. The simulated temperature curve of non-equilibrium model has a better agreement with the experimental results. However, the adiabatic system, the stable back pressure, and instantaneous response of the sensor are not that easy to be achieved, which leads to limitation on the monitoring of the experimental data. Hence, there are some deviations between the experimental results and the simulation results.

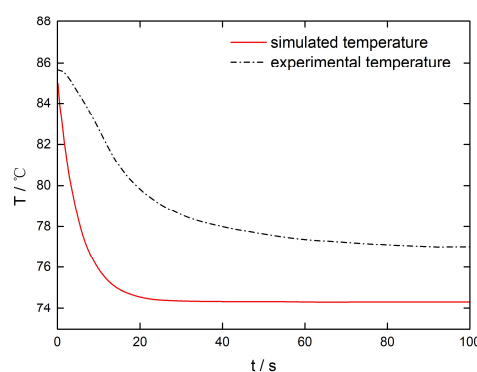


Figure 3. Temperature evolution of flashing

4. Conclusion

Based on the mass and energy conservation of vapor-liquid phase, the thermodynamic model of the two-phase in the flash chamber was established. The flashing process in the flash chamber was calculated and analysed by means of Simulink simulation. The simulation results show that the simulated pressure and temperature curves under different conditions agree well with the experimental data. In addition,

the non-equilibrium model has a better consistency than the equilibrium model. Therefore, the non-equilibrium thermodynamic model could predict the variation of parameters of the flash process, such as the temperature and pressure. Furthermore, it can be used in industrial applications and provide further support for the design of desalination vessels, the operation and optimization of marine steam accumulators, and the design of ship steam power system.

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