Chapter 04

Heat transfer with phase change

Reminder and types of devices

•The most common phase-change heat exchangers are: surface condensers with shell and tube bundle, coil condensers, reboilers, flooded evaporators or forced-circulation evaporators.

•A key feature is that, on the side where phase change occurs, the fluid temperature remains almost constant (pure saturated vapor), and the convective heat transfer coefficient is generally much higher than for single-phase cooling.

2.Condensation of a pure vapour

2.1. Filmwise condensation on the outside of tubes

•In filmwise condensation, the condensate forms a continuous liquid film that flows by gravity over the cold wall and creates an additional thermal resistance between the vapour and the wall.

•The film heat transfer coefficient for filmwise condensation on a single tube or a tube bundle is calculated using Nusselt-type correlations, as a function of the latent heat, the viscosity and thermal conductivity of the condensate, the wall–vapour temperature difference, and the geometry (diameter, length, number of tube rows).

2.2. Overall coefficient and simple condenser design

•The overall heat transfer coefficient U groups together the resistances: condensation film on the vapour side, conduction through the tube wall, convective film on the cooling-fluid side, and possible fouling layers.

•The simple design of a shell-and-tube surface condenser is carried out using $Q = UA\Delta T_{lm}$,where Q is the heat load to be condensed, A the heat transfer area and ΔT_{lm} the logarithmic mean temperature difference between the vapour and the cold fluid.

3.Desuperheating and condensate cooling

•In practice, the vapour often arrives superheated: there is therefore a first desuperheating zone (cooling of single-phase vapour), then a zone of isothermal condensation, and finally a zone where the condensate is cooled as subcooled liquid.

•Each zone has its own overall heat transfer coefficient and its own mean temperature difference; the complete design distributes the total heat transfer area among these three zones according to the thermal duties and the levels of U.

4.Condensation of a complex vapour (mixture)

4.1. Physical particularities

•For a mixture, the condensation temperature varies along the heat exchanger (non-isothermal condensation), and the presence of non-condensable components strongly degrades the heat transfer coefficient because of mass-diffusion effects.

•The Ward and Kern methods introduce a transfer coefficient specific to the condensable vapour, by correcting the energy balances to account for the additional resistance associated with non-condensable gases and with the composition profile.

4.2. Ward method (general idea)

•The Ward method expresses the heat flux as the sum of sensible and latent heat transfer, and introduces an additional diffusion resistance coupled with heat transfer, which leads to an apparent convective coefficient that is lower than in the case of a pure vapour.

•The coefficient specific to the condensable vapour is obtained by correcting the measured or calculated flux using the vapour mole fraction and the drop in partial pressure, which makes it possible to separate the effects of the non-condensable gas.

4.3. Kern method (general idea)

•The Kern method provides practical correlations to directly estimate an overall coefficient or a corrected vapour-side coefficient, based on dimensionless numbers and correction factors that account for the non-condensable fraction, tube-bundle geometry, and flow regime.

•It is often used in industrial design of mixture condensers when absolute accuracy is less critical than simplicity of calculation.

Pressure drop in the shell

The pressure drop in the shell side comes from the flow of vapour and condensate through the baffles and around the tube bundle, and it is calculated using friction factors together with geometrical correction factors (baffles, tube pitch, etc.).

These pressure drops determine the required size of safety or control valves, the height of the condensate column, and, in mixture condensation, the distribution of partial pressures and thus the condensation profile.