6.6.4 Chugging and condensation oscillations

An example of a dynamic instability involving a two-phase flow is that which causes the oscillations that occur when steam is forced down a vent into a pool of water. The situation is sketched in figure 1 and is clearly relevant to the pressure suppression systems used in BWRs (see section 7.4), a context in which the phenomena have been extensively studied (see, for example, Wade 1974, Koch and Karwat 1976, Class and Kadlec 1976, Andeen and Marks 1978). The phenomena do, however, also occur in other systems in which steam (or other vapor) is injected into a condensing liquid (Kiceniuk 1952). The instabilities that result from the dynamics of a condensation interface can take a number of forms including those known as *chugging* and *condensation oscillations*.

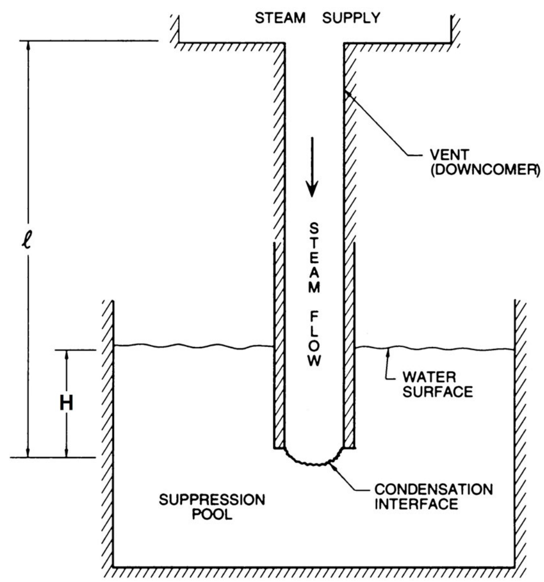

Figure 1: Components of a pressure suppression system.

The basic components of the system are as shown in figure 1 and consist of a vent or pipeline of length, ℓ, the end of which is submerged to a depth, H, in a pool of water. The basic instability is illustrated in figure 2. At relatively low steam flow rates the rate of condensation at the steam/water interface is sufficiently high that the interface remains within the vent. However, at higher flow rates the pressure in the steam increases and the interface is forced down and out of the end of the vent. When this happens both the interface area and the turbulent mixing in the vicinity of the interface increase dramatically. This greatly increases the condensation rate that, in turn, causes a marked reduction in the steam pressure. Thus the interface collapses back into the vent, often quite violently. Then the cycle of growth and collapse, of oscillation of the interface from a location inside the vent to one outside the end of the vent, is

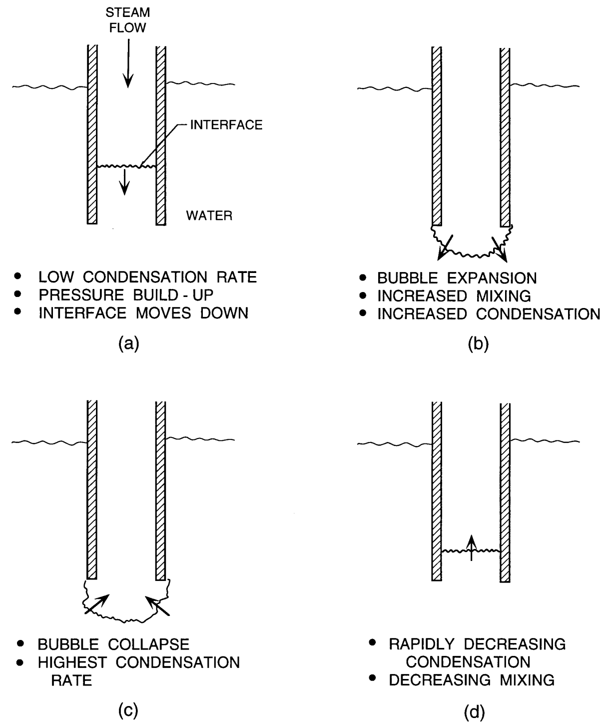

Figure 2: Sketches illustrating the stages of a condensation oscillation.

repeated. The phenomenon is termed condensation instability and, depending on the dominant frequency, the violent oscillations are known as *chugging* or *condensation oscillations* (Andeen and Marks 1978)

The frequency of the phenomenon tends to lock in on one of the natural modes of oscillation of the system in the absence of condensation. There are two obvious natural modes and frequencies. The first, is the manometer mode of the liquid inside the end of the vent. In the absence of any steam flow, this manometer mode will have a typical small amplitude frequency, $\omega_m = (g/H)^{\frac{1}{2}}$, where g is the acceleration due to gravity. This is usually a low frequency of the order of 1 Hz or less and, when the condensation instability locks into this low frequency, the phenomenon is known as *chugging*. The pressure oscillations resulting from chugging can be quite violent and can cause structural loads that are of concern to the safety engineer. Another natural mode is the first acoustic mode in the vent whose frequency, ω_a, is approximately given by $\pi c/\ell$ where c is the sound speed in the steam. There are also observations of lock-in to this higher frequency and these oscillations are known as *condensation oscillations*. They tend to be of smaller amplitude than the chugging oscillations.

Figure 3 illustrates the results of a linear stability analysis of the suppression

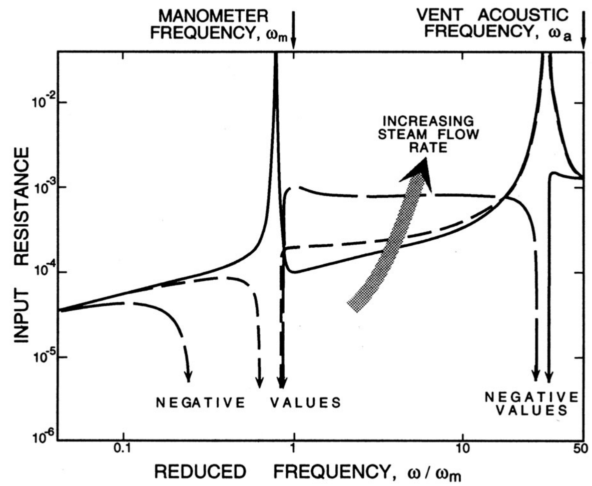

Figure 3: The real part of the input impedance (the input resistance) of the suppression pool as a function of the perturbation frequency for several steam flow rates. Adapted from Brennen (1979).

pool system (Brennen 1979). Constructing dynamic transfer functions for each basic component of this system (see Brennen 2005), one can calculate the linearized input impedance of the system viewed from the steam supply end of the vent. In such a linear stability analysis, a positive input resistance implies that the system is absorbing fluctuation energy and is therefore stable; a negative input resistance implies an unstable system. In figure 3, the input resistance is plotted against the perturbation frequency for several steam flow rates. Note that, at low steam flow rates, the system is stable for all frequencies. However, as the steam flow rate is increased, the system first becomes unstable over a narrow range of frequencies close to the manometer frequency, ω_m. Thus chugging is predicted to occur at some critical steam flow rate. At still higher flow rates, the system also becomes unstable over a narrow range of frequencies close to the first vent acoustic frequency, ω_a; thus the possibility of condensation oscillations is also predicted. Note that the quasistatic input resistance at small frequencies remains positive throughout and therefore the system is quasistatically stable for all steam flow rates. Thus, chugging and condensation oscillations are true, dynamic instabilities.

It is, however, important to observe that a linear stability analysis cannot model the highly non-linear processes that occur during a *chug* and, therefore, cannot provide information on the subject of most concern to the practical engineer, namely the magnitudes of the pressure excursions and the structural loads that result from these condensation instabilities. While models have been developed in an attempt to make these predictions (see, for example, Sargis *et al.* 1979) they are usually very specific to the particular problem under investigation. Often, they must also resort to empirical information on unknown factors such as the transient mixing and condensation rates.

Finally, note that these instabilities have been observed in other contexts. For example, when steam was injected into the wake of a streamlined underwater body in order to explore underwater jet propulsion, the flow became very unstable and oscillated wildly (Kiceniuk 1952).