Condensation Shocks

In the preceding sections we investigated nozzle flows in which the two components or phases are present throughout the flow. However, there are also important circumstances in expanding supersonic gas or vapor flows in which the initial expansion is single phase but in which the expansion isentrope subsequently crosses the saturated vapor/liquid line as sketched in figure 1. This can happen either in single component vapor flows or in gas flows containing some vapor. The result is that liquid droplets form in the flow and this cloud of droplets downstream of nucleation is often visible in the flow. Because of their visibility these condensation fronts came to be called condensation *shocks* in the literature. They are not, however, shock waves for no shock wave processes are involved. Indeed the term is quite misleading since condensation *fronts* occur during expansion rather than compression in the flow.

The detailed structure of condensation fronts and their effect upon the overall flow depends upon the nucleation dynamics and, as such is outside the scope of this book. For detailed analyses, the reader is referred to the reviews of Wegener and Mack (1958) and Hill (1966). Unlike the inverse phenomenon of formation of vapor bubbles in a liquid flow (cavitation - see section (Nhb)), the nucleation of liquid droplets during condensation is governed primarily by homogeneous nucleation rather than heterogeneous nucleation on dust particles. In a typical steam expansion $10^{15}/cm^3$ nuclei are spontaneously formed; this contrasts with the maximum credible concentration of dust particles of about $10^8/cm^3$ and consequently homogeneous nucleation predominates.

Homogeneous nucleation and the growth of the droplets require time and therefore, as indicated in figure 1, an interval of supersaturation occurs before the two-phase mixture adjusts back toward equilibrium saturated conditions. The rate of nucleation and the rate of growth of these droplets will vary with circumstances and may result in an abrupt or gradual departure from the isentrope and adjustment to saturated conditions. Also, it transpires that the primary effect on the flow is the heating of the flow due to the release of the latent heat of vaporization inherent in the formation of the droplets (Hill 1966). Typical data on this adjustment process is shown in figure 2 that includes experimental data on the departure from the initial isentrope for a series of six initial conditions. Also shown are the theoretical predictions using homogeneous nucleation theory.

For more recent work computing flows with condensation fronts the reader is referred, by way of example,

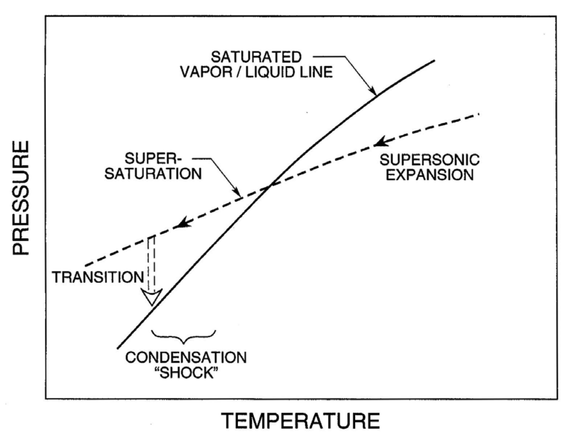

Figure 1: The occurence of condensation during expansion in a diffuser.

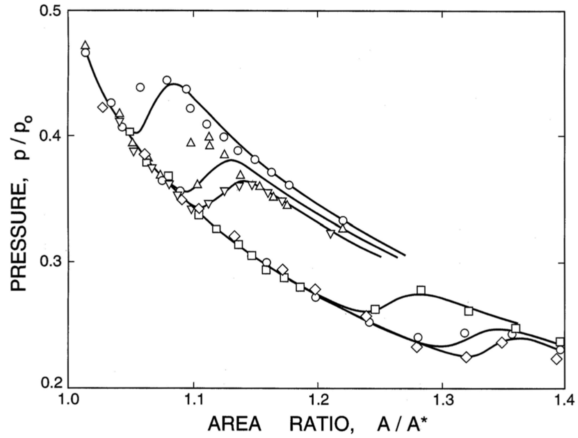

Figure 2: Experimental pressure profiles through condensation *fronts* in a diffuser for six different initial conditions. Also shown are the corresponding theoretical results. From Binnie and Green (1942) and Hill (1966).

Figure 3: Condensation *fronts* in the flow around a transonic F/A-18 Hornet operating in humid conditions. U.S. Navy photograph by Ensign John Gay.

to Delale *et al.* (1995). It also transpires that flows in diffusers with condensation fronts can generate instabilities that have no equivalent in single phase flow (Adam and Schnerr 1997).

Condensation fronts occur in both internal and external flows and can often be seen when aircraft operate in humid conditions. Figure 3 is a classic photograph of a US Navy F/A-18 Hornet traveling at transonic speeds in which condensation fronts can be observed in the expansion around the cockpit cowling and downstream of the expansion in the flow around the wings. Moreover, the droplets can be seen to be re-evaporated when they are compressed as they pass through the recompression shock at the trailing edge of the wings.