Chapter 5

Results and Discussion

5.1 Introduction

The development work presented in the previous chapters yielded a FORTRAN program (See Appendix A) which could simulate two-phase ejector flow for a variety of inlet conditions. In tandem with the code is an experimental ejector test rig (see Sec. 1.2.1) which can be run at conditions approximating those of an EERC system. The ejector is fitted with pressure taps along its length to measure pressure rise in the mixing section and diffuser. The test rig could thus supply experimental verification for the code in the form of pressure profiles for the mixing section, which is the essential performance measure of the ejector.

Along with pressure rise, several other variables either used by or output from the code are important in studying the fluid mechanics occuring within the ejector. These are droplet diameter exiting the motive nozzle and its distribution once inside the mixing section, the velocity profiles of liquid and vapor, and the distribution of liquid across the radial domain of the mixing section. Also important are constants used by the code for the mixing length turbulence model. These variables will be examined with a view toward their effect on ejector design.

However, the use of the code in running flow simulations of the ejector was limited by two unexpected phenomena. The first is a shock-like effect occuring inside the motive nozzle in which the flow regime changes suddenly from bubbly to droplet. The second is recirculation in the mixing section. Neither of these phenomena, which are discussed at length below, can be handled by the code in its present form. Thus, the code could run non-recirculating cases of flow in the mixing section only.

Other results to be discussed are numerical in nature. These include numerical accuracy considerations, CPU time for the code, and convergence difficulties experienced during code execution.

5.1.1 Flow Regime Transition Shock

The shock-like effect mentioned above has been named the flow regime transition shock (FRTS), a theory advanced by Kornhauser [49] based on the experimental work of Bunch [11] and Harrell [23]. According to this theory, the flow first consists of a bubbly mixture as it expands in the motive nozzle. Conditions for the mixture are close to HEM since the bubbles readily move at the same velocity as the continuous liquid, and the high surface area of the dispersion creates enough heat transfer to keep up with thermal equilibrium requirements. The bubbly flow goes through the throat, which is choked, and expands supersonically in the diverging section of the nozzle (the HEM speed of sound applies here, which is much lower than either the vapor or liquid separately). Here, the bubbles have grown to the point where the flow regime is actually foamy. Now, a transition takes place to the droplet flow which has been observed exiting the motive nozzle. Since the speed of sound of the flow now approximates that of continuous vapor, the flow is essentially subsonic, and the vapor slows down as it compresses through the rest of the section. The liquid droplets, however, maintain their original velocity at the shock, since their higher density gives them a great deal of inertia. Thus, the flow exiting the motive nozzle consists of high velocity droplets in a much slower vapor. Harrell [23] has noted that this high slip flow exiting the motive nozzle is required in order to obtain the subsequent mixing section pressure rise that he has measured experimentally. Harrell has written a 1-D model to simulate the FRTS and the flow in the mixing section.

For the two-phase flow code produced here, the difficulty with the FRTS lies in the supersonic flow occurring upstream of the shock. The code cannot handle supersonic flows since, generally, different methods are required for such flows (for one, the code would need to solve the energy equation, which was omitted due to time constraints). The code would treat the region upstream of the shock as a single phase HEM flow. However, in so doing, it would require a criterion for conversion to a subsonic droplet flow since it cannot by itself determine the two-phase flow regime.

Since this information is the essence of the FRTS, the code in its present form would be unable to handle it. Furthermore, it is unclear that even if it could, that it would produce any better results than Harrell's 1-D model of the phenomenon. Although adjustments to the code should be made to incorporate this effect, it is left for future work since other serious problems were discovered in the mixing section.

5.1.2 Recirculation

Operation of the ejector test rig by Harrell [23] at first yielded anomalous pressure profiles in the mixing section. For a typical case, Fig. 5.1 shows how pressure rises very little or falls at the first tap after the inlet, and then begins to rise normally. It was expected that pressure rise would begin immediately because the greatest mixing would occur immediately.

These pressure profiles are believed by to be the result of flow recirculation in the mixing section. A similar delay in pressure rise is observed in single phase mixing sections which are known to be recirculating (Hill, [50]). The separation bubble acts like a nozzle

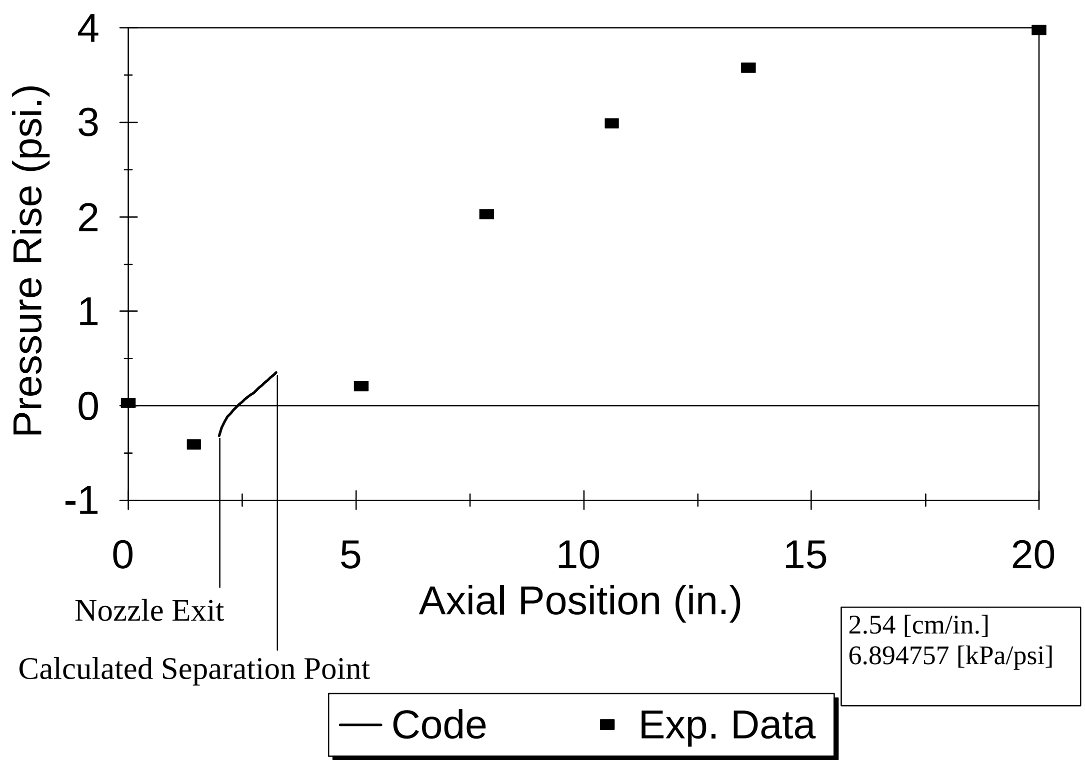

Figure 5.1 - Code vs. Experiment with Separation (Original Ejector)

which counteracts the tendency toward pressure rise as the flow mixes.

Furthermore, results of this two-phase flow code predict the observed recirculation by ceasing computation at the point where the wall shear stress approaches zero. Fig. 5.1 shows the pressure profile of the code overlaid on Harrell's experimental results for a short section. According to the code, recirculation has occurred where the pressure profile stops.

The basic reason for separation lies in the rate at which mixing occurs and causes pressure rise. For large differences in momentum between the motive and suction flows, the mixing rate will be high and so the corresponding pressure rise will also be high. This effect tends to decrease the wall shear required to satisfy a momentum balance across the duct and drives the flow toward separation. A dimensionless parameter known as the Hill number has been used to predict recirculation in single-phase flows. It can be extended as follows to two-phase flow:

$$H=\left[\frac{\frac{\dot{m}_{total}}{A_{total}}\left(\frac{\dot{m}_{suction}}{\rho_{suction}}+\frac{\dot{m}_{liquid}}{\rho_{liquid}}+\frac{\dot{m}_{vapor}}{\rho_{vapor}}\right)}{\dot{m}_{suction}\,V_{suction}+\dot{m}_{liquid}\,V_{liquid}+\dot{m}_{vapor}\,V_{vapor}}\right]^{1/2} \tag{5.1}$$

This expression essentially represents the momentum of the flow if suction and motive velocities were equal divided by the momentum of the flow at the actual, unequal velocities. Thus, lower Hill numbers mean a higher tendency to recirculate. Since the motive momentum is much higher in two-phase flow because of the presence of the higher density liquid, this expression has a generally lower value in two-phase flow than in single-phase flow. However, it is not known what values of Hill number, if any, correspond to separation in two-phase flow. Furthermore, it is possible that another non-dimensional number, or a more complex expression, would be required for accurate prediction of recirculation in two-phase flow. Nonetheless, the Hill number does show the basic physical mechanism involved.

If flow recirculation is occurring in the mixing section, the pressure rise data obtained cannot be used to validate the code. As explained earlier, the parabolic nature of the code makes it impossible to compute past the separation point. Since it was not originally thought that recirculation would occur in the ejector (any reasonable ejector design would avoid separation), no provision in the code was made to handle it. Indeed, by making the parabolic approximation in the first place, the idea of computing through recirculation regions was essentially ruled out.

The experimental mixing section, which was believed to exhibit recirculation, originally had the dimensions shown in Fig. 5.2. Harrell's data for this section and code results, both indicate recirculation is taking place. No code results are available for this body of experimental data except up to the separation point. A second mixing section, characterized by a long tapered converging angle was installed and gave unclear results.
A similar delay in pressure rise was observed but it was never certain if this was because of recirculation or because of the convergence of the mixing section itself. Code results for this case exhibited convergence difficulties which may be related to approaching the separation point, although execution stopped well upstream of separation. This problem was not fully investigated.

These difficulties led to the design of another, smaller diameter, mixing section, which is believed to avoid recirculation altogether. As discussed below, this new section produced non-recirculating results which could be used for code verification.

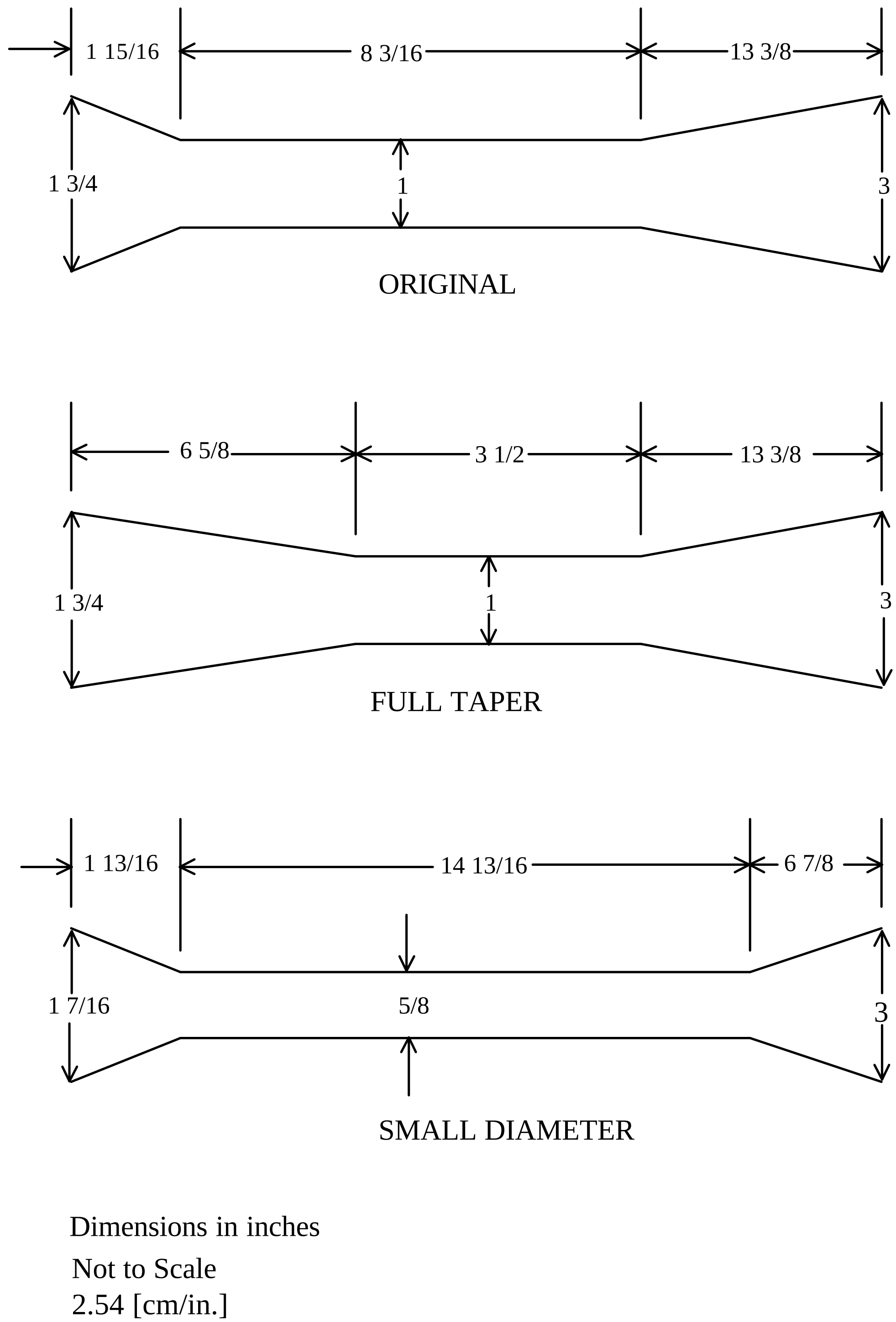

Figure 5.2 - Experimental Mixing Sections

5.1.3 Limitations of the Code

The problems associated with recirculation and, to a lesser extent, the FRTS, limited the use of the code considerably. Originally, it was intended that the code be used to solve for the flow in the bubbly flow tube, motive nozzle, mixing section, and diffuser. The suction nozzle would be solved by standard single phase methods, since the flow there consists of superheated vapor. However, the new understanding of flow conditions described above hindered progress in finding a complete numerical solution for the entire ejector.

Hence, results of the code have not been made for the motive nozzle or diffuser (which shows an even greater tendency to separate). Also, the code does not solve the energy equation or have features related to it such as compressibility and interfacial mass transfer. Nonetheless, since the results here are limited to the mixing section, it is felt that in any case, momentum transfer there is a more important effect than energy transfer. It is expected that the energy equation plays a greater role in the motive nozzle where supersonic velocities and a high degree of thermal non-equilibrium are present.

Given these reasons, it was felt that an effort should be made to understand the flow in the mixing section, particularly the separation effect which was noticed. Since experimental results without separation have been forthcoming, it has been possible to check the code against experimental data.