under the influence of wall shear and interfacial mixing in an expected manner. The liquid and vapor profiles immediately move closer together and the sharp gradient near the wall, characteristic of highly turbulent flow, is also quickly established. In fact, the velocity gradient near the wall is the same as for a single phase flow, since no liquid actually reaches the wall (an issue which will be discussed further below).

5.2.3 Results Concerning Liquid Droplet Distribution

Despite this fact, there is a liquid velocity profile calculated up to the wall. Initially, in the annular region, the liquid void fraction is set to be negligibly small. Thus, it is phantom liquid, created artificially to prevent having to set up an inconvenient internal boundary condition between the region of the liquid jet and the outer annular vapor.

This artifice brings up an important point in the modelling of the interfacial drag. One of the inputs to the interfacial drag equation (Eqn. 3.1) is the droplet diameter. Initially this value was assumed constant throughout the flow, as would be the case in solid particle flow. However, in the suction region where no real liquid exists, assuming this value to be the same as for the rest of the flow decreases the interfacial drag (since droplet diameter is large compared to the nearly zero value of void fraction) to the point where it is negligible. The phantom liquid then can and does have a velocity greater than that of the vapor (see Fig. 5.10) since its viscous interaction with the liquid in the central part of the jet overcomes the interfacial drag force (which tends to keep it at the same velocity as the vapor). This situation is physically unrealistic primarily because in a region of negligible liquid there is not enough mass to produce even one droplet of the size assumed in the central jet. The "droplets" in the negligible liquid region should be much smaller than in the central region of the jet. According to Eqn. 3.1, smaller droplet diameter leads to a greater interfacial drag force, which would in turn cause the liquid and vapor velocity profiles to be closer together than what is shown in Fig. 5.10.

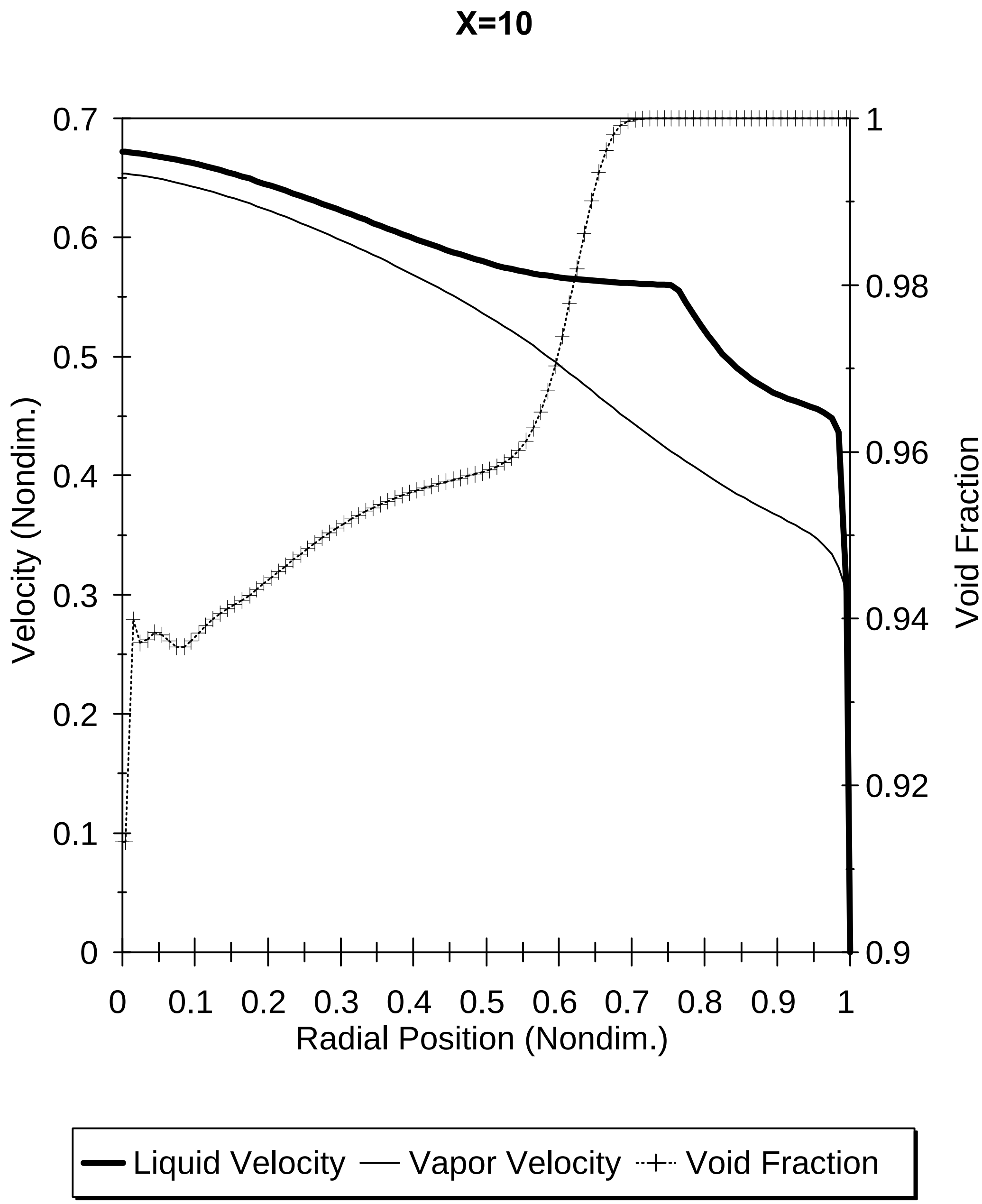

Figure 5.10 - Velocity Profile for Constant Droplet Diameter

If smaller droplets are to be used in the annular region of negligible liquid, how should their size be determined? In this case it was assumed, for simplicity, that the ratio of liquid volume fraction to droplet diameter was a constant, based on the value in the central part of the jet flow. Thus, as the liquid void fraction approaches zero, so does the droplet diameter.

Figure 5.11 shows a liquid velocity distribution where this assumption is used. Here, a large droplet diameter (d=.004) is used down to a liquid void fraction of $1X10^{-4}$. For void fractions smaller than this value, the constant ratio of void fraction to droplet diameter is invoked. In this constant ratio region the interfacial drag force is large, which keeps the liquid velocity very close to that of the vapor. In Fig. 5.11 this region begins around a radial position of 0.7 and extends to 1.0. Hence, the liquid velocity profile is indistinguishable from the vapor profile in this region. Below the radial position of 0.7, the liquid velocity profile is the same as in Fig. 5.10, where the droplet diameter is everwhere constant.

One feature of both Figure's 5.10 and 5.11 is the flattening out of the liquid velocity profile as the liquid void fraction approaches zero (note that this corresponds to a vapor void fraction approaching unity, as shown in the figures). The flat portion of the profile is then followed by a discontinuity beyond which the profile is actually in the region of negligible liquid. The flattening out effect makes sense physically because the region of negligible liquid imposes no shear stress on the liquid in the core region. This situation is similar to the flat velocity profile which would occur in wall flow where wall shear has been set to zero. Furthermore, since the liquid void fraction is approaching zero as the profile flattens out, the interfacial drag becomes ever smaller. Thus, the liquid profile tends to deviate from the vapor profile (unlike in Fig. 5.6) and flatten out.

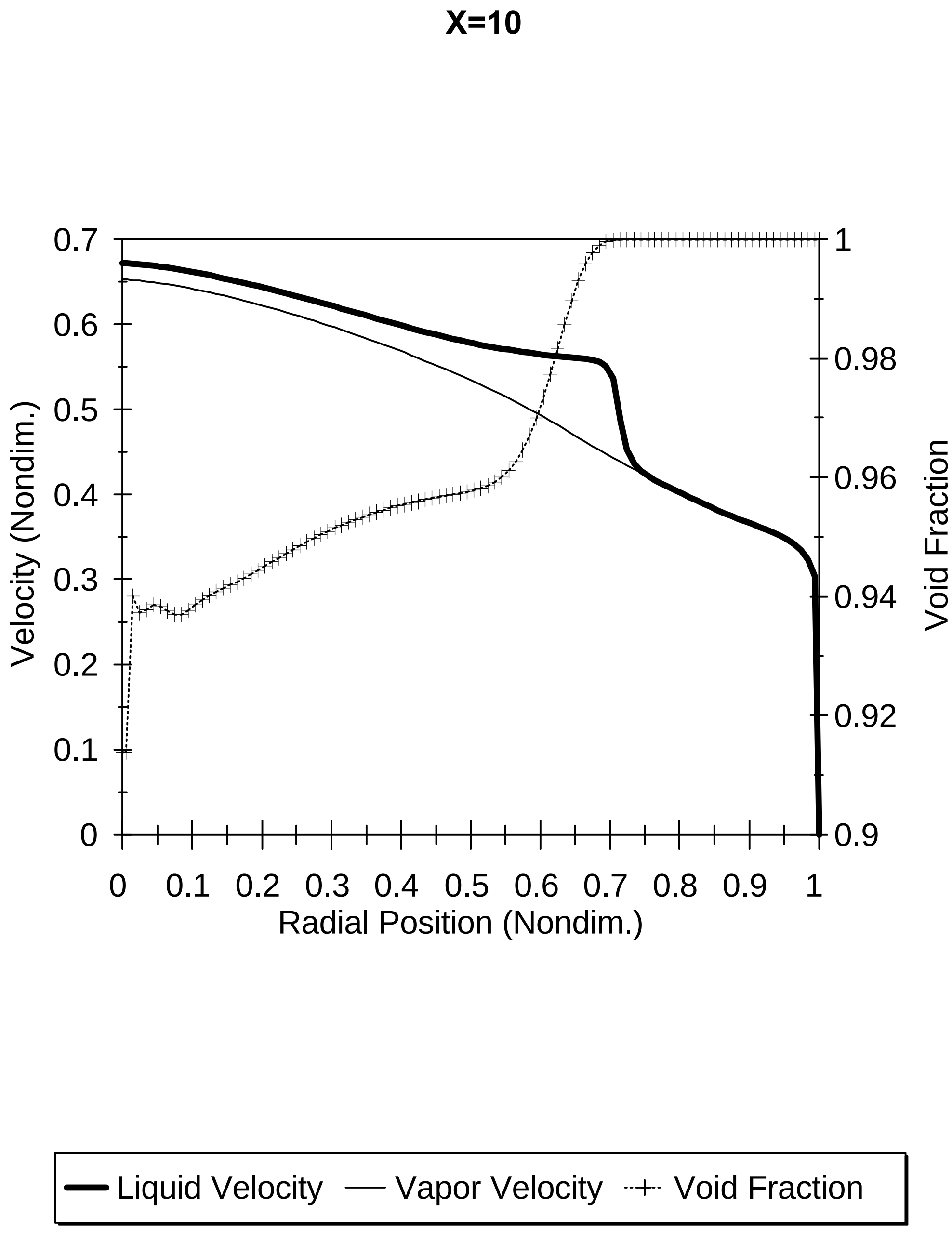

Figure 5.11 - Velocity Profile for Constant Droplet Diameter
up to Region of Negligible Liquid

If variable droplet size is to be introduced in the annular region, is it not reasonable to introduce it in the central jet region as well? It seems especially appropriate to do so at the boundary between the central jet and the annular vapor region, where liquid void fraction is approaching zero, but not quite negligible (for the same reason as given above). Furthermore, it is physically realistic to assume smaller droplet sizes in regions of high shear, such as exists in this boundary region. Thus, regions of higher liquid void fraction and lower shear would have larger droplet sizes. Although it is not known what the relationship between shear, void fraction, and droplet size should be (another topic for future work), here it was again assumed, mainly for convenience, that the variation was such that the ratio of void fraction to droplet diameter is constant.

Thus, it is assumed that throughout the flow this constant ratio holds, not just in the region of negligible liquid (as in Fig. 5.11). This assumption is used in the velocity profiles shown in Figs. 5.6-5.9, and in all the results shown after Fig. 5.11. In Fig. 5.6 it should be noted that the liquid profile tends to follow the vapor even as the void fraction approaches zero (it does not flatten out as in Figs. 5.10 and 5.11). This effect illustrates that for any variation of void fraction, the interfacial drag will remain significant because of the constant ratio of void fraction to droplet diameter.

Besides liquid velocity profiles, the most interesting result is the distribution of liquid across the domain. The expected distribution for any high velocity spray of liquid droplets emanating from a nozzle is eventual mixing of the droplets with the rest of the flow and spreading of the droplets throughout the duct. Code results, however, report that at the beginning of the duct, the liquid spray actually tends to concentrate more along the centerline (Fig. 5.12), the exact opposite trend from what is expected. Further downstream, however, this trend seems to die out and is replaced by a small spreading of the liquid into the annular region. Two points can be made about this effect:

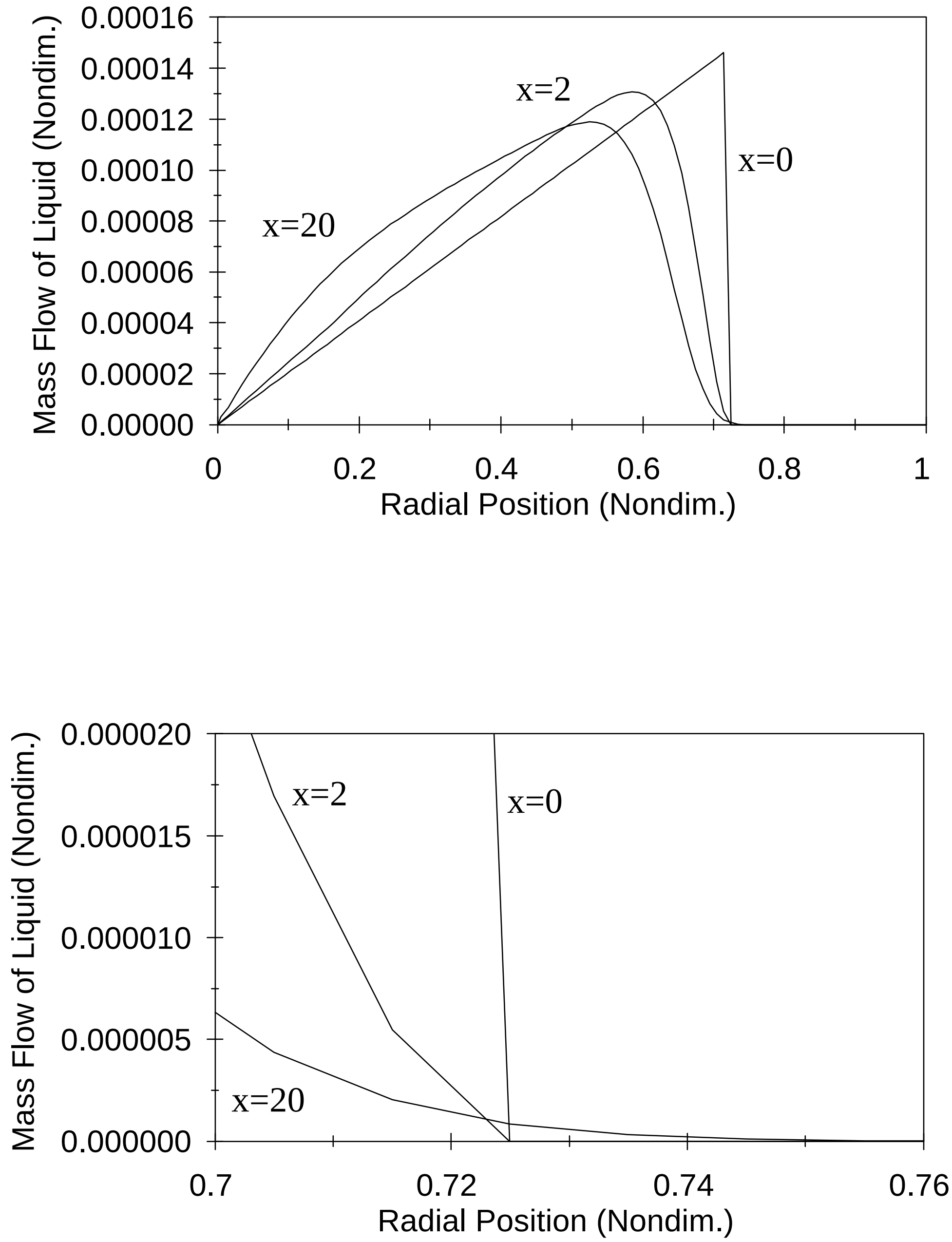

Figure 5.12 - Liquid Mass Distribution Across Domain with Closeup View

1. Because of the flat initial velocity profile, and the sudden imposition of the no-slip condition at the duct wall, the radial velocity gradient that is set up to satisfy continuity is especially sharp. This gradient pushes vapor toward the axis of symmetry due to the slowing down of the vapor near the wall. This pronounced negative (toward the axis of symmetry) radial velocity of vapor drags liquid with it. Figure 5.13 illustrates this radial velocity profile at an axial step close to the inlet (x=1) and close to the outlet (x=15). Near the inlet, the pronounced negative vapor velocity is evident, along with its effect on the liquid. Eventually, however, the wall gradient is established and the radial velocity profile approaches zero, as it would in any developing pipe flow. Now, since the liquid jet continues to slow down as it interacts with the slower vapor, its natural tendency to expand outward reasserts itself (see lower graph of Fig. 5.12). The amount to which it does so, however, is small since the density of the liquid is so much greater than the surrounding vapor. It is possible that using more realistic profiles at the inlet to the section would aid in spreading into the periphery faster, but it is unlikely to have dramatic results simply because, as a highly turbulent flow, the flat inlet profile is not a totally unrealistic assumption.
2. Although the motive nozzle has some divergence which would cause an outward radial velocity gradient at the inlet to the duct, the assumed profile did not take this into account. This was done in order to be consistent with Harrell's 1-D code, in which an initial profile is assumed to get the correct slip. Furthermore it is not clear what radial velocity gradient to use without actually solving for the flow in the motive nozzle. Finally, although some more investigation should be undertaken on this point, some preliminary runs with inlet radial velocity distributions failed to give significantly different liquid profiles in the duct.

Another issue concerning the liquid distribution is the downward spike in the void fraction profiles near the centerline in Figs. 5.6 and 5.10. It is not clear what causes the

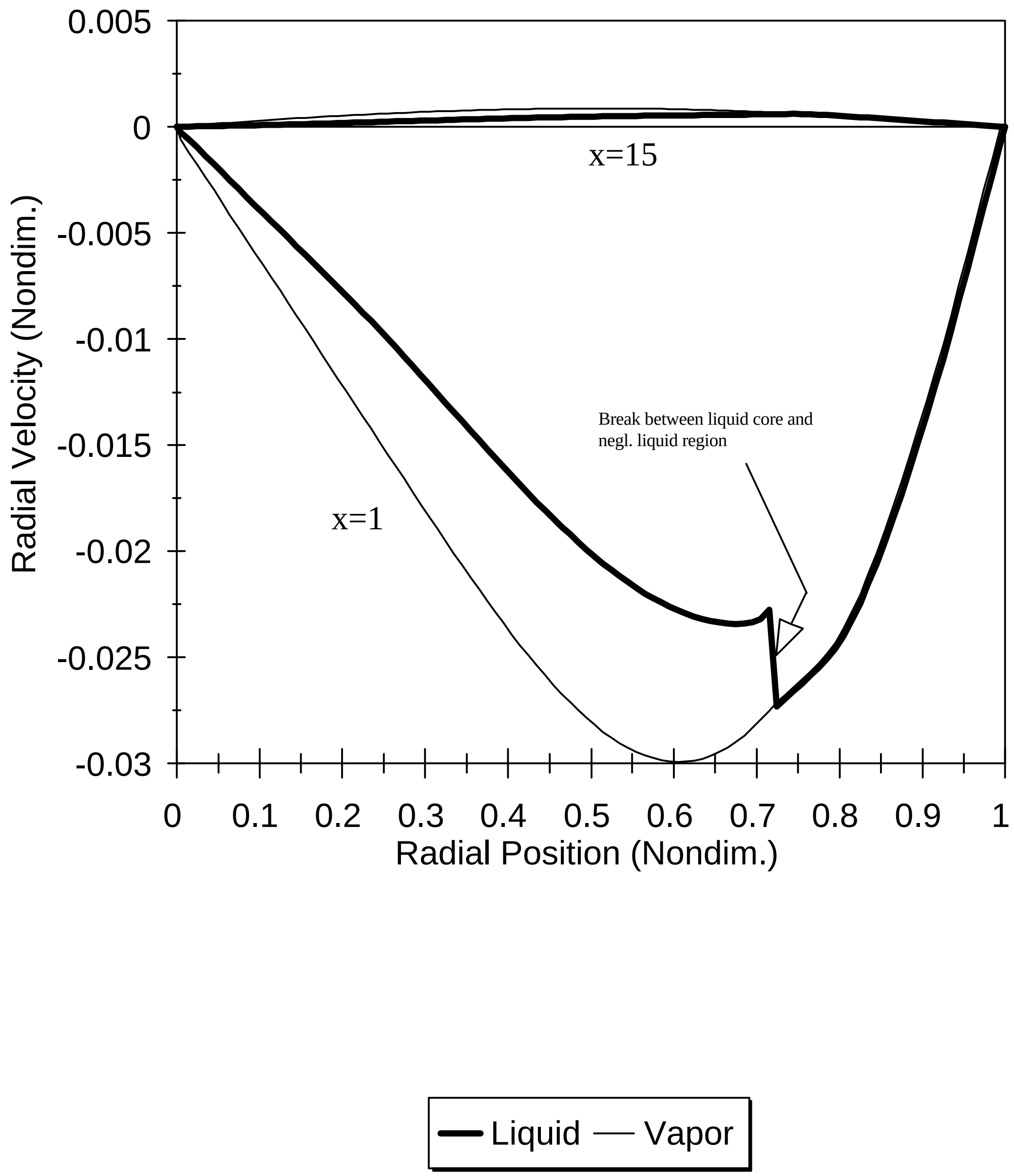

Figure 5.13 - Variation of Radial Velocity