INTEGRATION OF EJECTORS INTO HIGH-SPEED AIRCRAFT

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The subject I will talk about is of interest in the sense that most of the studies and analyses that are done on the ejectors are for static case and do not attend to the forebody effects. Because most of the ejectors are mounted on something, we might call the analysis that we have essentially isolated ejector analysis.

Now everything that we normally see in these analyses is what we might call rectilinear mixing; in other words, we assume that the two flows, the primary and the secondary, are more or less parallel. But even a very small pressure differential could create a curvature in the flow, and then the rectilinear mixing has to be modified to account for the curvature. For example, this would modify the eddy viscosity, and in cases where you have coanda jet, the flow will be completely asymmetric. There is no asymmetric in the flow at all inside the ejector. In addition to this, when the forebody is put in there, the flow that enters the ejector is not a very simple flow. So we have the question, what happens? We spend money developing a beautiful ejector producing 2.5 to 3 augmentation. Then we put it on a machine that we would like to fly and find it doesn't work. The problem that I am talking about is essentially the integration of ejectors into aircraft (fig. 1).

In general terms, what I am saying is valid whether you're considering subsonic, transonic, supersonic, or whatever sonic you're considering because you always have the same problems except that there may be differences in the actual flow field. For the purpose of illustration, I have just shown here two cases: one for the transonic and one for the supersonic case. As far as the forebody is concerned, it could be either a fuselage, a wing, a nacelle, or anything. It doesn't matter. I have just shown a type of airfoil situation there.

Before we look into the flow field that is shown there, let us first cancel the transonic case. In the transonic situation the flow that enters into the ejector is that flow which is downstream of the shock boundary-layer interaction region. If there is no shock wave, in other words, we have a smooth supersonic flow, then we still have a boundary layer that enters into the ejector. Depending on the width and the thickness of the boundary layer the flow that enters into the ejector will have a very nonuniform flow. Even if you consider a situation where you don't have a boundary layer, you still have the pressure field due to the forebody which is not uniform necessarily in front of the ejector. Also, if you consider the upper and lower sides, the pressure distribution is not necessarily the same all the time, so you have asymmetry. All these factors are very important in finding out whether the ejector will do what we want it to do, as far as the inlet portion of the ejector is concerned.

With the exit portion we have to consider the question of matching between the flow inside and outside — the external flow coming over the ejector flap and that which is coming from inside where they are mixing. So this is the other aspect that is very important in analyzing the integration of the ejector into the aircraft. Below I show a situation where we have a supersonic flow. Of course, under these conditions you have a bow shock, then subsonic region, then a sonic and a supersonic flow. This can shock down into the ejector. All these things are going to make a lot of difference. If the flow inside is supersonic, it will have to match that external flow through Prandtl-Meyer expansion. All these things are very important in terms of the actual usages of an ejector, whether it be in flight or hover, in transition, or a few minutes after takeoff while it's going up — wherever there's a flow over the forebody.

What we are really saying is that the whole problem should be looked into as a single problem. Of course, one can divide up the analysis of each of these items separately. For example, one can develop a mixing analysis for the flow inside, just as I have seen several very nice analyses today. Or you might just develop an external aerodynamics analysis to present what the flow would look like outside. But then these have to be matched together in order to get the actual flow field and see whether the ejector will do the job we want it to do. Naturally we'll also be interested in finding out whether we could design an ejector for a given type of pressure distribution in the exit plane, which means that we should be able to modify the shape of the ejector flaps or the forebody, whatever it be.

This is a problem that we think is very important, and in my review for all the available literature, I haven't come across anything that has been done to this end. Consequently, we have developed a methodology on how to do the various aspects. I'm going to talk about those, and of course we are interested in finding someone who might be interesting in supporting it. The way we say it can be done is, for example, I was talking about boundary-layer mixing; this is the type of thing that has primary and secondary flows, so when I say parallel, I don't mean exactly parallel — there could be slight differences in angle. But whenever there are pressure differentials between the lower and upper, or anywhere, there is going to be a correction ΔP which is simply related to the curvature of the flow. So the curvature is very important. What I'm going to show is the work we have done in this connection as a starting point. The work is connected with taking into account the effect of curvature on the mixing inside a given duct, and that's what I'm going to show in the next few figures. After I will show how we have developed a methodology to match the external and internal flows for a simple case of a kind of average velocity assumed on these two slides two different velocities, naturally. Then we'll examine the methodology for predicting the flow field over a system like this (fig. 2).

Now here we are considering a situation where we have a differential between the secondary and the primary, and this leads naturally to correcting the flow. The mixing region will be curved, and the flow within the duct will be entirely nonsymmetric. It is quite possible that the jet boundary will reach the wall either on the lower or upper side first, and this makes a difference as to what kind of pressure profile you're going to have within the duct. Also, depending on the length of the duct, the pressure profile at the exit then is going to be different. Here this is just nomenclature to show: η_{ui} simply means the inner jet boundary, etc. Now our analysis modifies the eddy viscosity to account for the curvature, and with that we have some results which I will show.

Figure 3 shows essentially the various types of nonuniformity that you can find within an ejector, depending on what type of curvature you have in the initial flow region. For example, the upper jet boundary may reach the wall earlier or later. The main jet itself may extend beyond the point where the lower and upper boundaries reach the walls. Each of these makes a different type of nonuniformity. Even if you have a pipe-type of flow where everything is turbulent, you still have a nonuniform profile.

In figure 4(a) we have taken a duct inclined to a primary at 45°, and we have considered a centerline jet of 100 ft/sec, about 40 ft/sec on the top, and 20 ft/sec on the bottom. This produces a certain curvature. You can see that the lower jet already reaches the wall much before the upper jet boundary reaches the wall. The center line is also curved, but it naturally uncurves itself as soon as it reaches the lower boundary. You can see that there is already a nonuniformity. For example, the secondary flow that is coming from outside and this is all the mixed turbulent flow.

Figure 4(b) shows the velocity distribution at the three places. We have a hundred ft per second centerline velocity decaying naturally as you go along the duct. You can see that the centerline velocity and the velocity in the lower boundary become almost equal. But the upper velocity does not it still takes a lot of time. For example, in this case, at 8 ft we still haven't reached equilibrium or a completely mixed flow yet.

Figure 4(c) shows the pressure distribution. This is a pressure which is initially constant in the jet-core region, and the pressure increases as we go down along the duct and this line. Both the pressures on either side are like that; you see the difference is very small. You can see also that even that small difference (less than a pound or half a pound) could still produce a curvature that has very large effect on the flow field within the duct. Figure 4(d) shows what happens to the velocity profile within the duct. To start with, you have the natural top hat, but an asymmetric top hat, because the velocities are not the same on both sides. They gradually mix so that the inviscid core is gradually annihilated. Finally, it reaches the area where the mixing is taking place. Hereafter there is a situation where one side has reached the wall and the other side has not reached the wall. This shows the velocity profile in the duct.

Essentially what these figures show is that even a small amount of pressure differential across the primary could lead to very important effects within the duct with many nonuniformities. Any analysis of ejectors should take this fact into account, and the question of matching becomes more urgent because it cannot match and simply say the pressure is ambient outside. Then you'll have a very long ejector — 100 ft longer or 200 ft longer — before you reach complete matching of pressures from either side.

Figure 5 shows the other aspect of which I was talking. Namely, how do you know what flow or what velocity should be there in the inlet portion, in order to arrive at a matched pressure at the exit plane? Of course, we developed the methodology, and it depends on what we call parametric differentiation. It started with the usual differential equations of all the flow. Each of the variables is a function for the geometries of the pressures of the initial velocities, and so on. You can differentiate each of the flow equations and come up with a set of equations which are functions of the parametric planes. Here I am showing, for example, a simple situation where you assume that the flow velocity on one side is U_{1g} and on the other side is U_{2g} ("g" for guess). You get a pressure from that, then you integrate the basic and parametric differential equations. You can use several analyses or parametric methods, and you come down to the exit plane and ask whether the pressure difference on the lower side is less than a given value. If it is less, see what happens on the upper side. But also, if it's the correct thing, no problem. Otherwise, you have to correct the initial guess that U_{1g} is corrected by the factor ΔU_{1g} which comes out of this solution. As we proceed along the ΔU that we calculated at the end and that can be substituted, you get a new value of the U_{1g} and U_{2g}. You go ahead and iterate until you get a convergent solution. This is the second aspect of how to match these two things. Of course, I have done it for a single velocity on either side, but this could be done for a velocity distribution. You can assume that U_{1g} is like an average velocity and you have a certain distribution over that place. You can still do the same thing.

The third aspect that I will talk about is shown in figure 6 -- the external aerodynamics. Here we are considering a simple forebody. You can have any type of forebody -- you can have a nacelle if you want. You can still do the same type of work. What we're simply showing, for example, is the stagnation streamline of the forebody. There are two stagnation streamlines off the ejector flaps in the two-dimensional case. It simply shows the amount of in-flow that is ingested into the ejector from the top and the bottom. Then you have a certain jet that is coming out of the exit plane. This jet naturally is also going to produce some lift, as you have seen in the paper by Bevelaqua, considering this particular aspect. I won't go into any great detail except to say that in the analysis for ϕ the velocity potential, ψ is the stream function and, as you know, the circulation is related to the $\Delta\phi$ jump. If you take two points on a particular line on this jet, they don't have the same potential. There will be a potential jump between those two points.

This methodology is valid for high subsonic and also small supersonic flows that have no shocks. But if you have shocks, then the analysis that I have to talk about here must be modified. The center will have to come up with some other method, like transonic analysis, that is available right now, many numerical analyses using relaxation methods. But this is valid for subsonic incompressible flow up to high subsonic speeds, and you don't have to make any changes in the methodology — it remains the same. It becomes very simple for incompressible flow, and the methodology is very similar to Spence's work. What you essentially do from this physical plane is go into a complex potential plane where the airfoil and the augmentor flaps and the jet become a cut on the ξ axis. You see this, of course, is the jump because of the amount of flow ingested into the ejector. This distribution is essentially the amount that has been ingested at different points around the boundary. From there we can transform this to another situation where it becomes just a simple cut on the ζ axis, real axis. We can make another transformation so that the whole flow field, essentially the upper portion of the semi-infinite plane, with the airfoil and the jet being reduced to a small piece D' to D' on the axis.

There are different methods. For example, this morning you heard of a method of how to account for the flap which was a one-sided flap in the paper by Mr. Woolard. Those methods all assume that the ejector is very thin almost like one singular line. This method that we have developed here, however, is valid even if you get a very thick jet. The boundary condition matching happens right at each of the upper trailing edges and lower trailing edges of the ejector flaps. Pressure matching has to be done there. Also, for example, if one wants to design something; say that I give you this kind of pressure distribution, why don't you give me what the ejector should look like, what the forebody should look like. That can be done. You can impose the pressure distribution that is required in one of these planes. The pressure distribution is translated into the velocity which you impose and that way you can do this work. Of course this leads to integral differential equations that have to be solved and this is where we are right now. We have reached the stage where all the equations will double up then, and it is a question of implementing the equations, writing the difference equations, and so on.

One point I want to make very clear is what happens to B' to C'. Let me get that number, what is it? Which is the boundary? What are the flow velocities there, etc. Now this is essentially where this matching analysis comes: the matching procedure. You start at a certain distribution of U_{1g} or U_{2g} on either side, then carry out the matching procedure to find out what this means in terms of the pressure differential at the end. If it's wrong, then you proceed. The important point essentially is that once you assume a certain thing, go ahead and compute the whole flow field, and match it to the ejector exit plane. Then whatever is happening here becomes part of the solution.

In summary, we feel that it is very important to do this analysis and take the integration of ejectors into whatever forebody you are having, from the beginning. At the same time you should have isolated ejector analysis, experiments, and things like that to get them up to beautiful augmentations. Thank you very much.

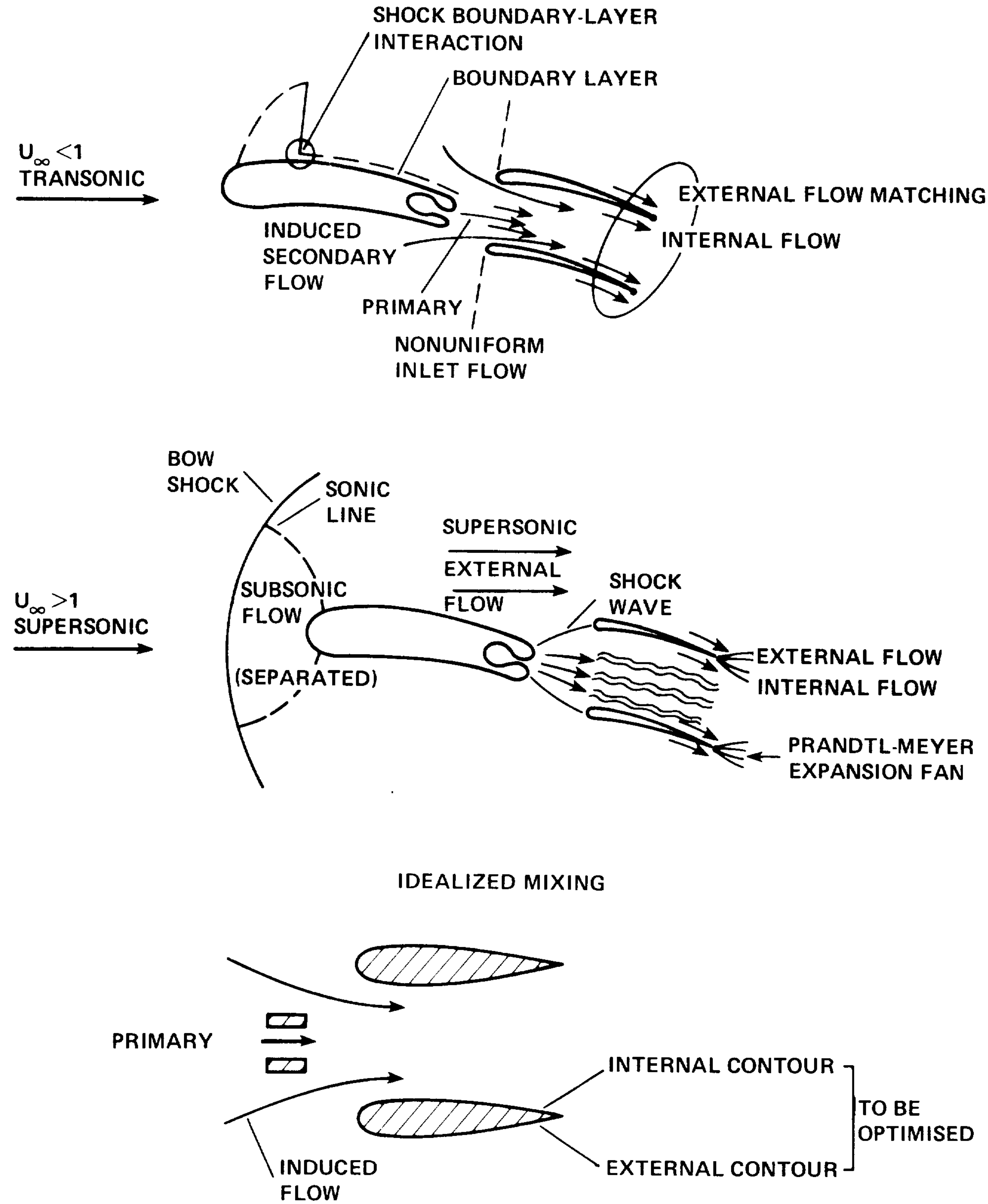


Figure 1.- Schematic of ejector integration problem.

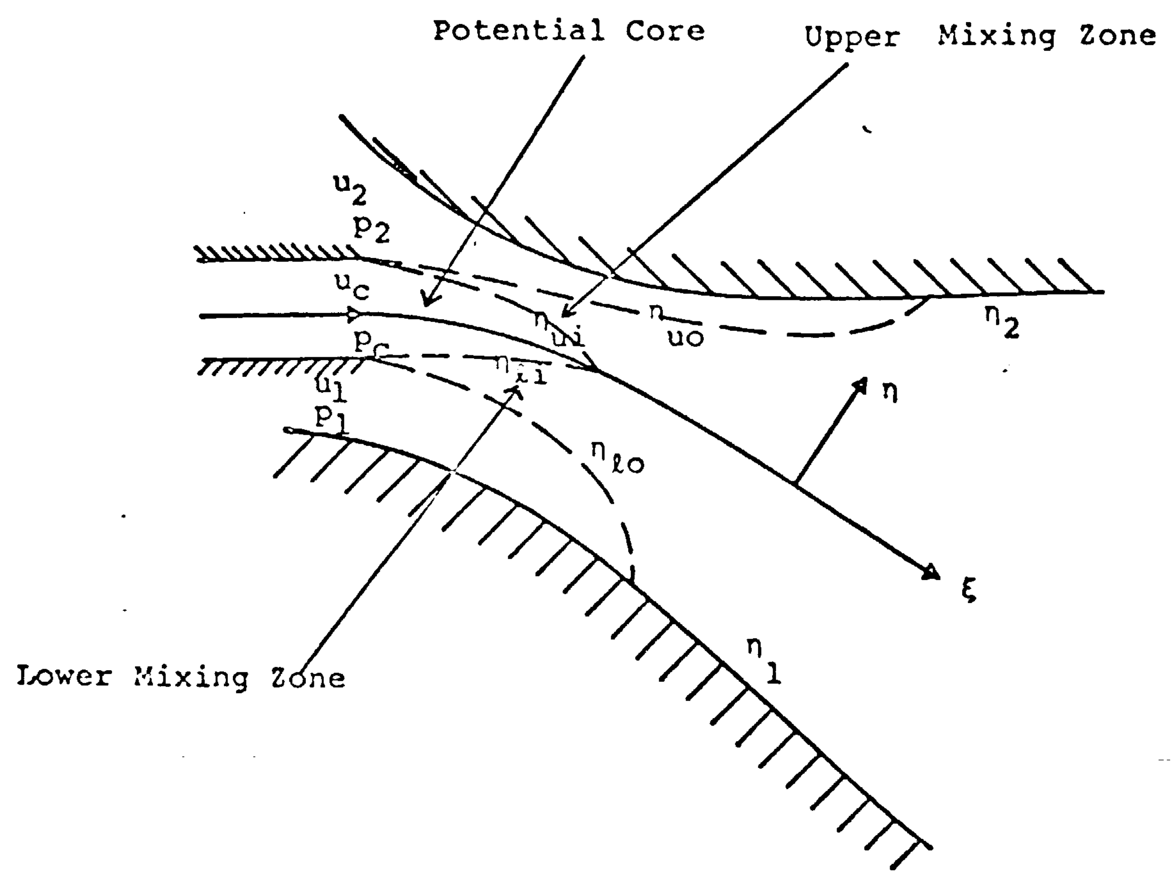


Figure 2.- Schematic of the flow field of ducted jet mixing for nonsymmetric secondary flow.

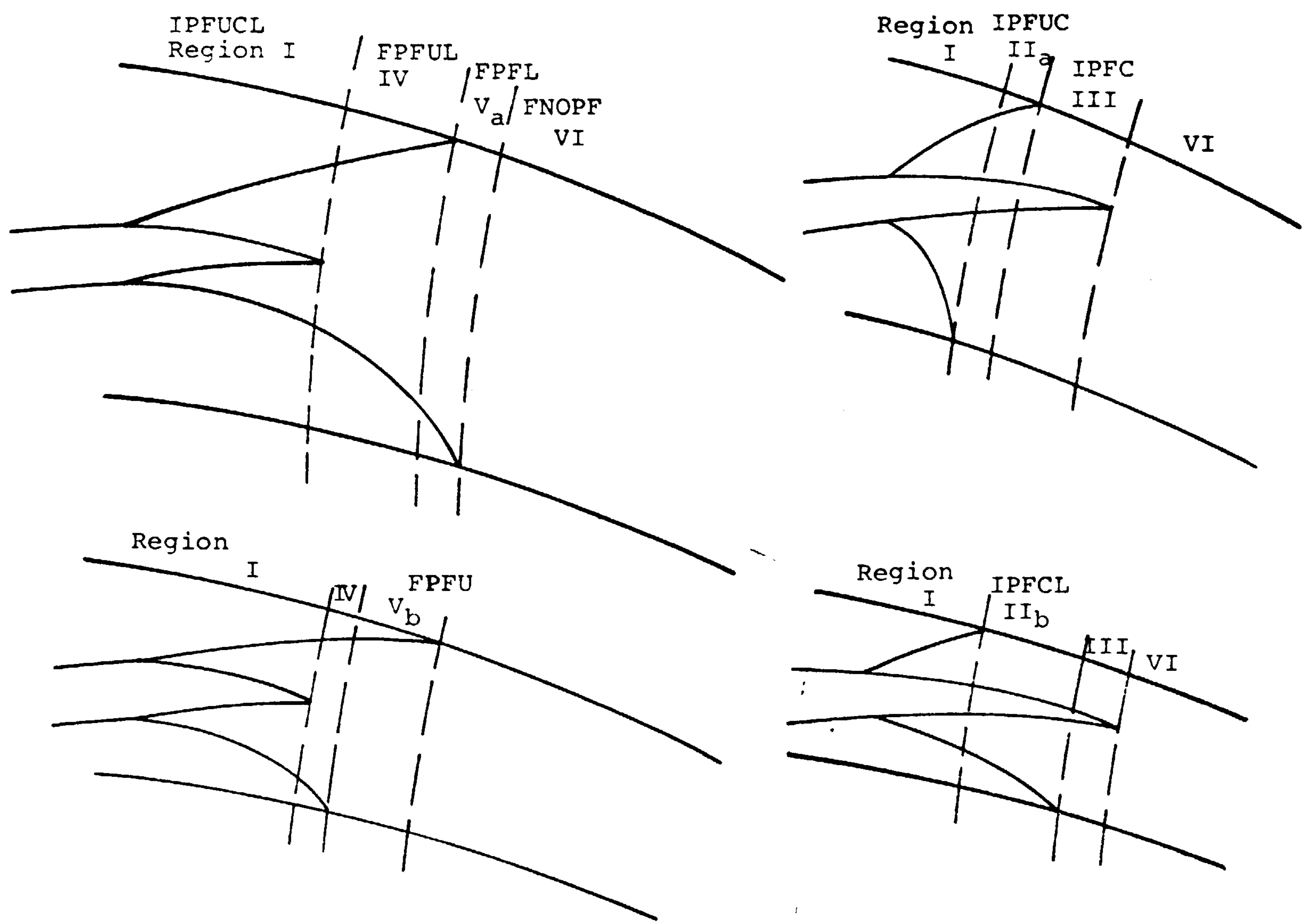
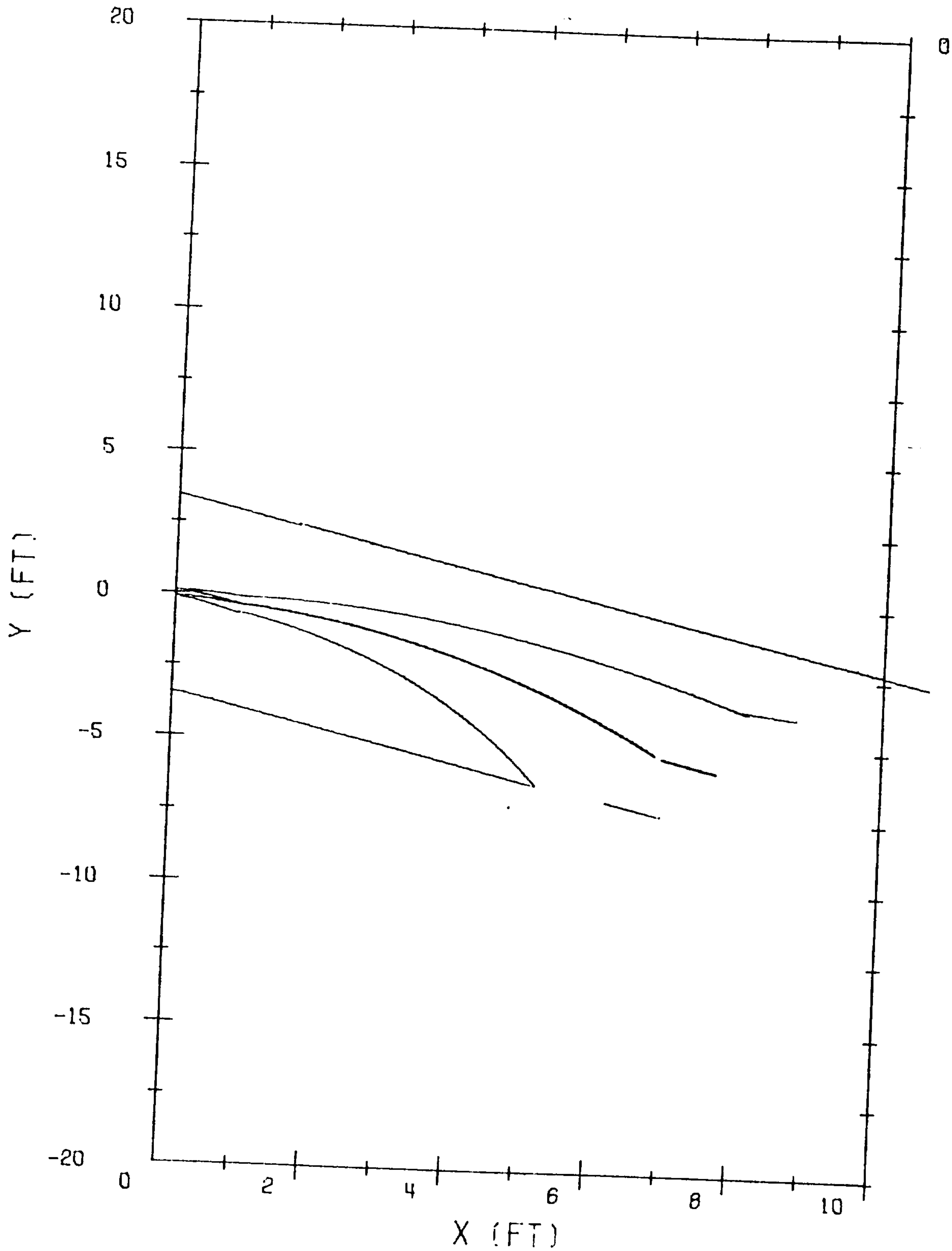
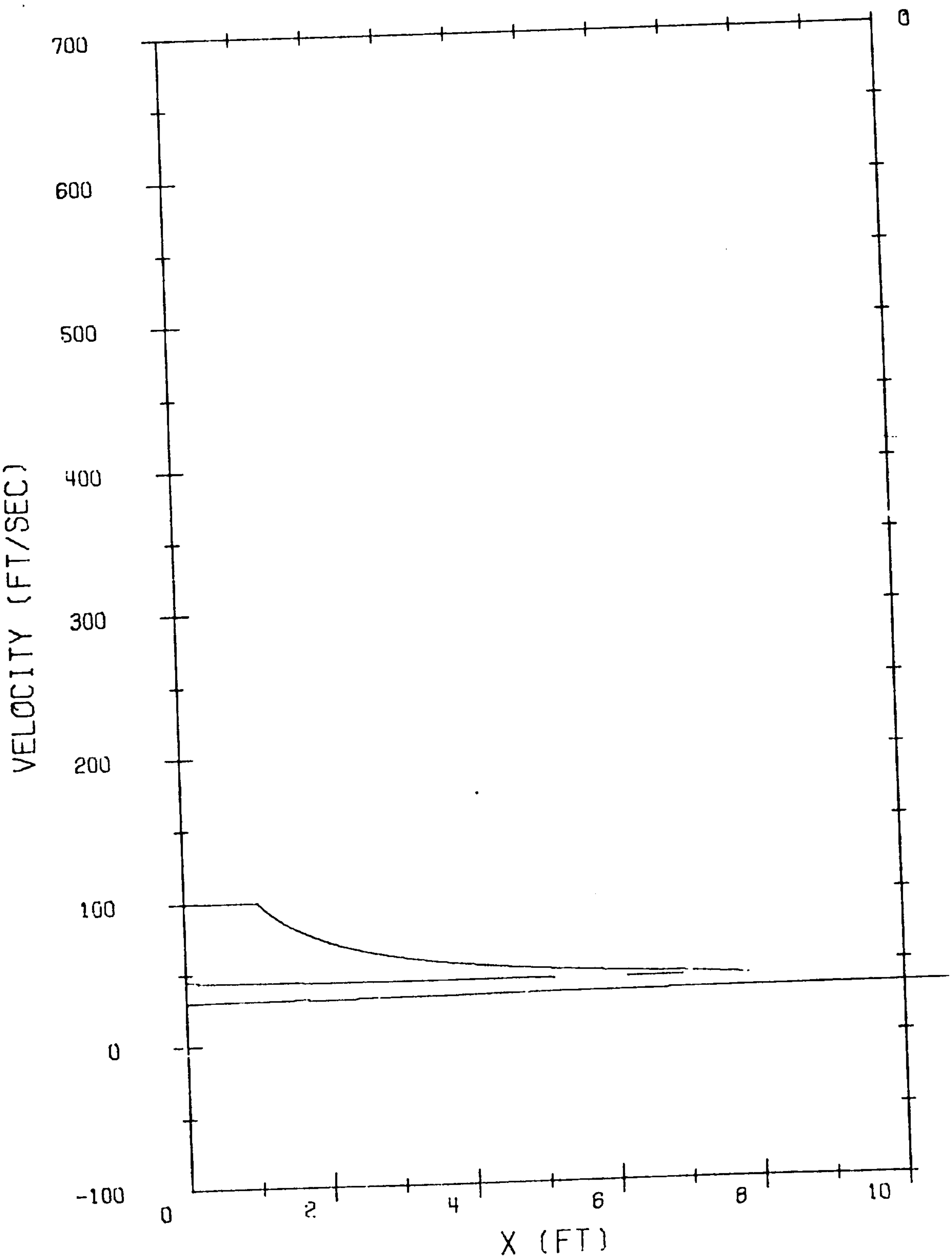


Figure 3.- The various flow regions.



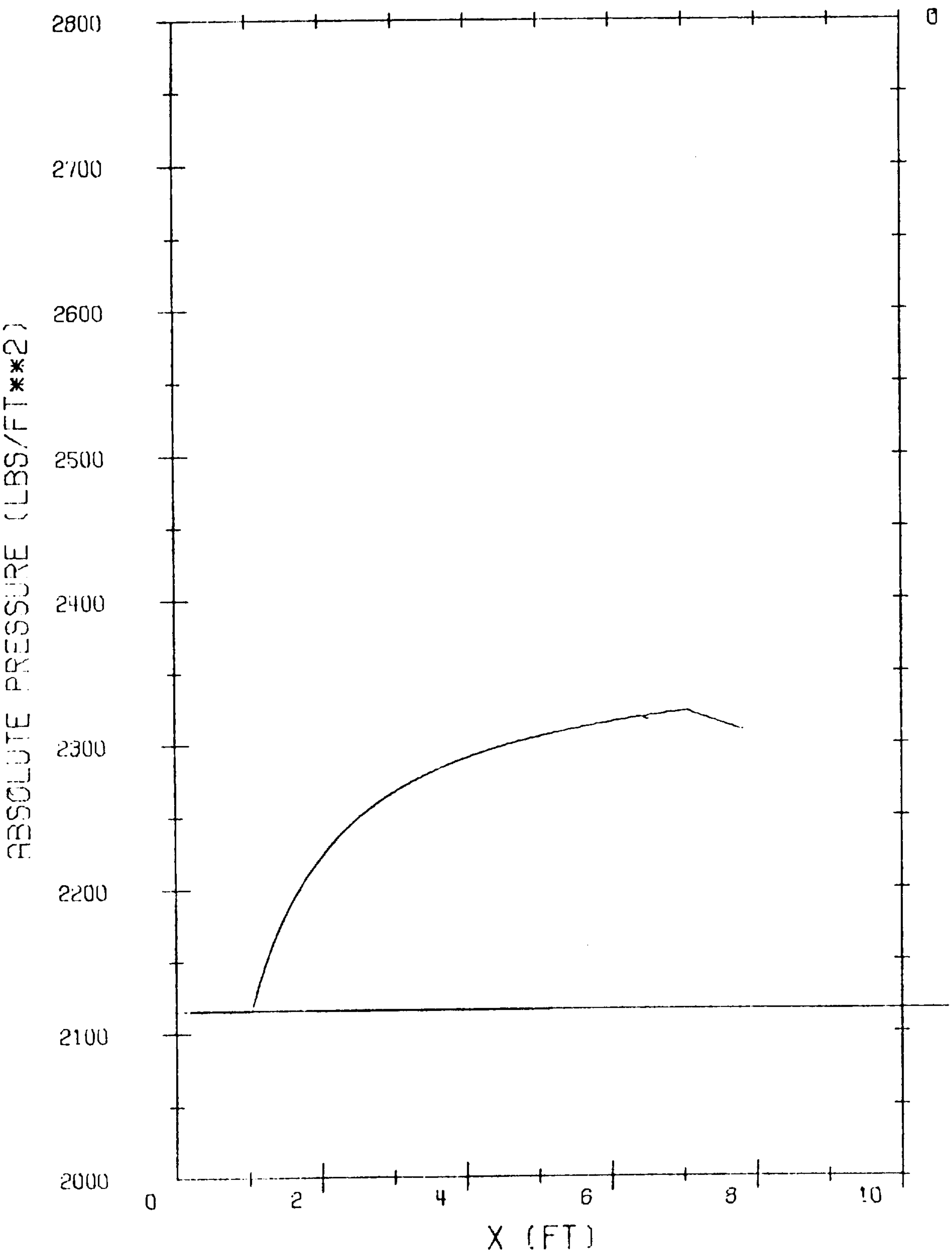
(a) Jet mixing zone boundaries, jet centerline and mixing duct walls.

Figure 4.- Flow-field characteristics inside the duct. Inclined ducted jet mixing; table V, case 11.



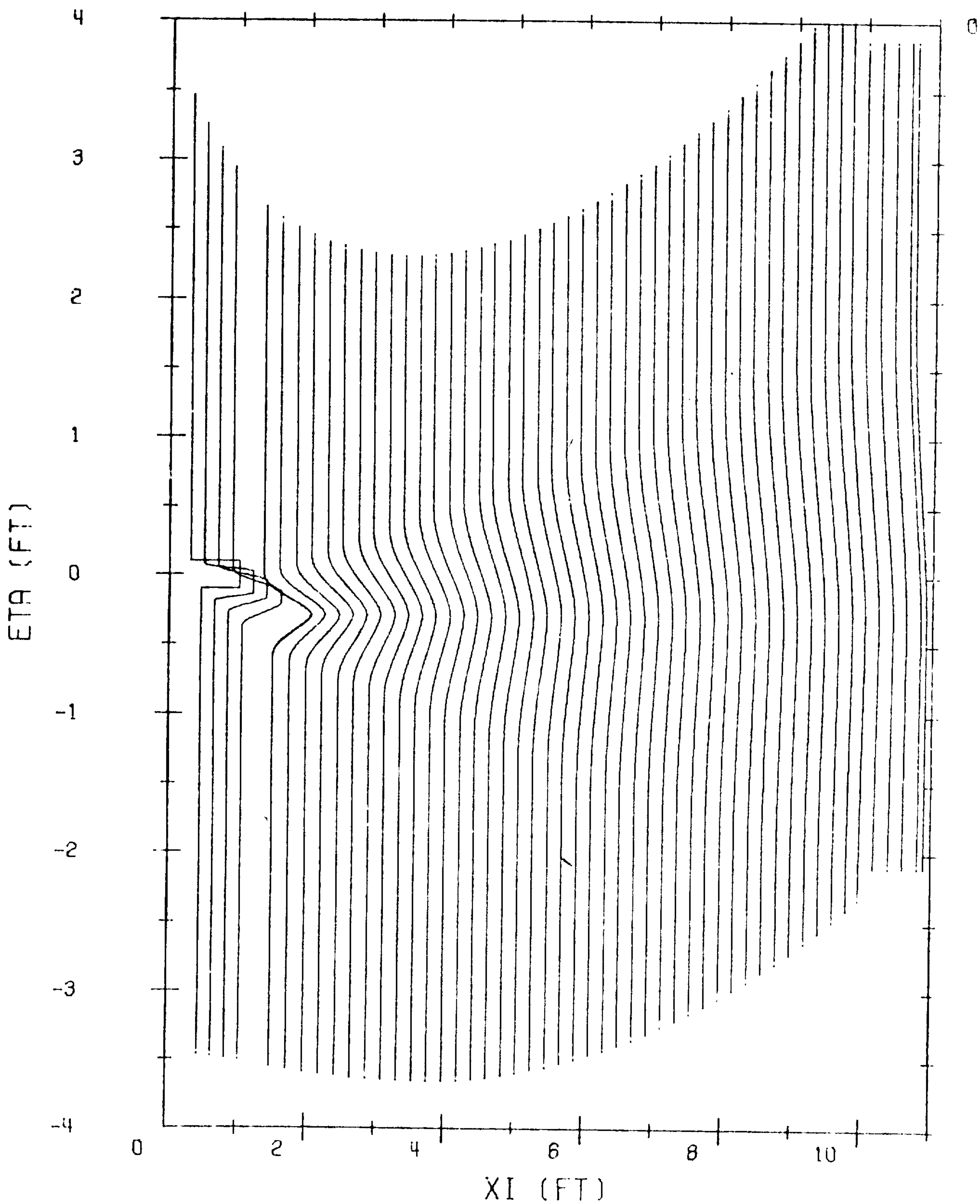
(b) Velocity distribution along the jet centerline and along the upper and lower duct walls.

Figure 4.- Continued.



(c) Pressure distribution along the jet centerline and along the upper and lower duct walls.

Figure 4.- Continued.



(d) Velocity profile across the mixing duct for increasing distance along the jet centerline ξ.

Figure 4.- Concluded.

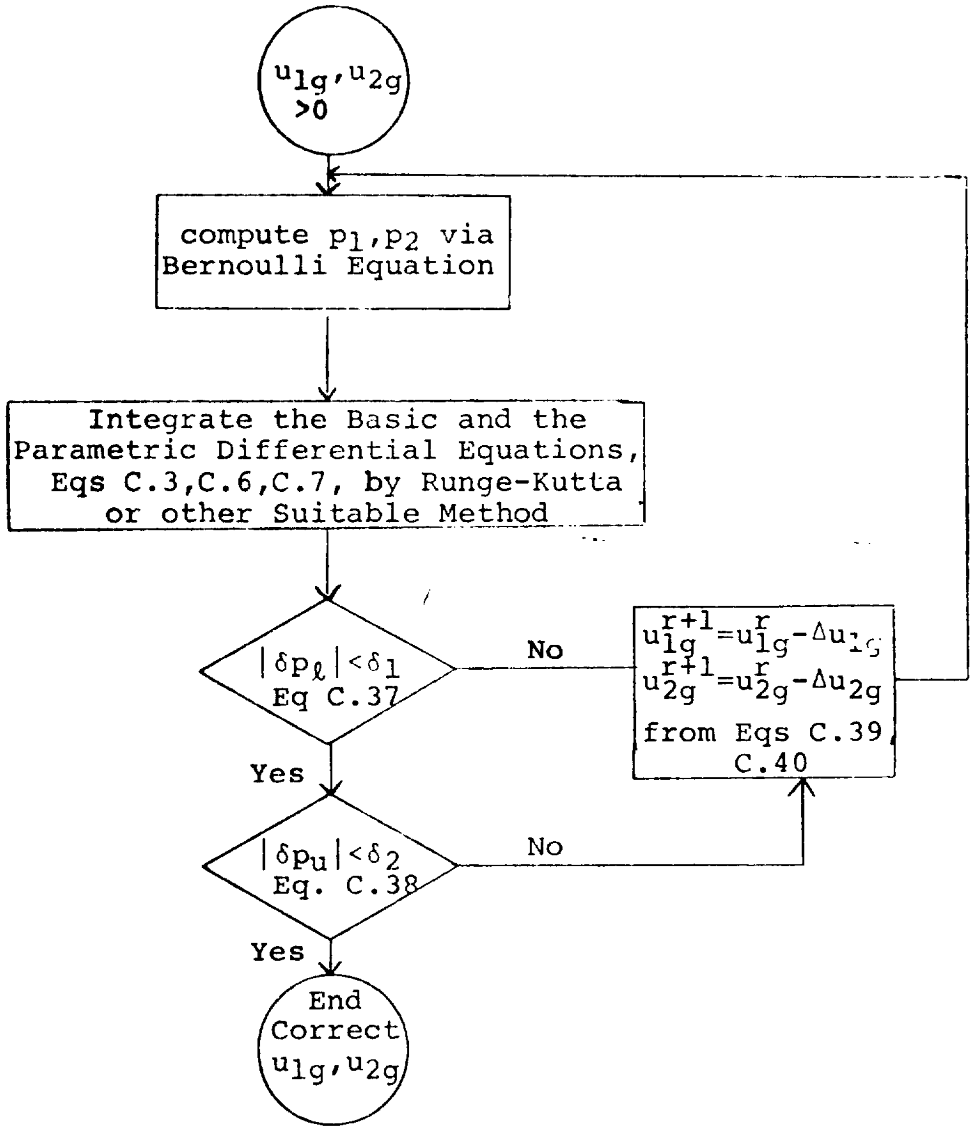


Figure 5.- Flow chart for the iterative solution to determine correct entrainment velocities of secondary flow at the mixing duct entrance.

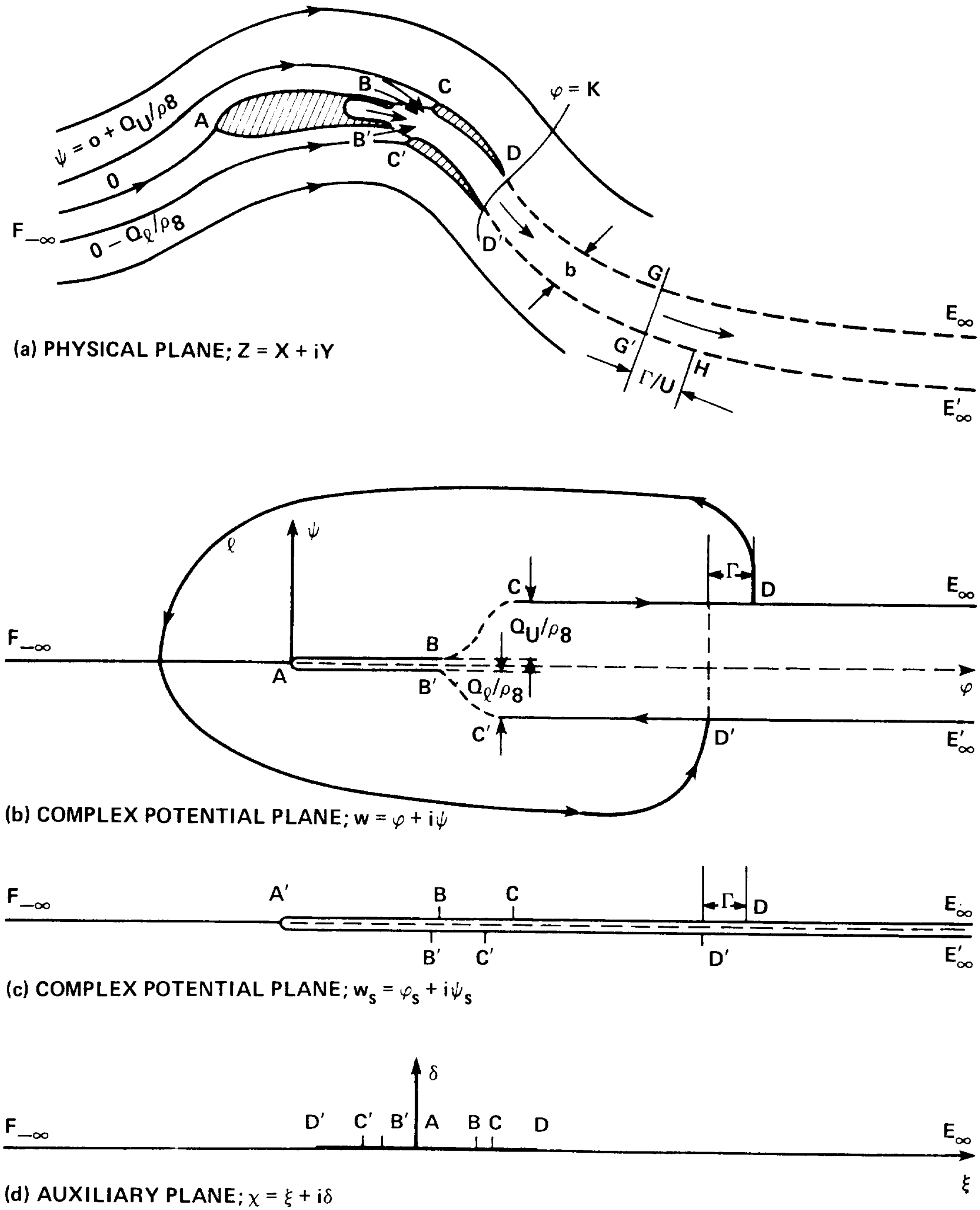


Figure 6.- The problem in Z, w, w_s and χ planes; nomenclature.