Chapter 8

Closure

Initially in this chapter, the conclusions drawn from the research described in this thesis will be presented and finally the potential avenues of further research will be discussed.

8.1 Conclusions

In this section, the major conclusions of the thesis will be presented. A number of the conclusions have been drawn earlier in the thesis as the theoretical and numerical analyses were performed but they are represented here in summation.

8.1.1 Elemental comparisons

With specific regard to mechanical problems exhibiting elasto-visco-plastic material behaviour, it has been illustrated that for the Constant Strain Triangular (CST) and Linear Tetrahedral (LT) elements, the FVM and the FEM as described in this thesis are directly equivalent. This equivalence was first proven theoretically in Chapter 4 and then illustrated numerically in Chapter 5.

From these conclusions it can be postulated that the direct equivalence of the two methods with regard to the linear elements will apply generally for all solid mechanics problems involving material non-linearity. Thus strengthening the position of the FVM as an alternative to the FEM for problems involving non-linear material behaviour. The close agreement of the two dimensional Bi-Linear Quadrilateral (BLQ) and three dimensional Bi-Linear Pentahedral (BLP) and Tri-Linear Hexahedral (TLH) elements also illustrates the effectiveness of the FVM for the said problems. A tentative conclusion can be drawn after close inspection of the results for the higher order elements as employed in the solid mechanical validation problems of Chapter 5. There is discernible evidence that the FVM appears marginally closer to the numerical reference solutions of non-linear problems when the plastic or visco-plastic strains are large and the non-linearity is greatest.

8.1.2 Surface tractions

When surface tractions or pressure loads are applied over a higher order face element, as in the case of TLH elements employed in the spherical vessel problem of Chapter 5, the FVM appears superior with regard to accuracy on a coarse mesh. As the mesh is refined both methods approach the reference solution and the superiority of the FVM with regard to accuracy is less significant. This superiority is also true for linear elastic problems and has been commented upon by Wheel [100], who considered plane elasto-static problems involving non-uniform stress and strain distribution. It can be argued that the superiority is associated with the discretisation and the definition of the control volumes employed in the FVM. In the FVM the constitutive variables, such as stress and visco-plastic strain, are equivalent at control volume boundaries. This is a direct result of the conservative approach to the control volume definition. This is not the case in the FEM, where the weighting functions employed do not ensure that the constitutive variables are equal at the control volume boundaries [43, 42, 4, 100, 31, 48].

The FVM appears to be closer to the reference solution in these cases, but these cases are limited and further numerical and theoretical analysis must be performed before any definitive conclusions can be drawn. It is also important to note that any improvement in accuracy furnished by the FVM appears to be offset against a considerable increase in computational cost when compared to the FEM, as again illustrated in Chapter 5.

8.1.3 Thermo-mechanical problems

With regard to the coupling of mechanical analyses involving non-linear materials, specifically those that behave elasto-visco-plastically, and thermal analyses involving such phenomena as fluid flow, heat transfer and solidification, the suitability of the three dimensional FV framework PHYSICA as a realistic option for this purpose has been further illustrated. The validity of the thermo-mechanical coupling technique employed within this framework is indicated by the results of the standard benchmark problems as described in Chapters 6 and 7. It should be noted that the staggered coupling technique described and employed in this research, though widely used in many applications, is not suitable for all thermo-mechanical problems, particularly those involving large deformations.

These achievements and conclusions lend weight to the selection of a FV framework for the numerical analyses of complex industrial processes involving a variety of complex physical behaviour. This point is reinforced by the potential of PHYSICA to comprehensively simulate the shape casting of metals as presented in Chapter 7.

8.1.4 Finite volume discretisation

At present within the PHYSICA framework the heat transfer employs a cell-centred FVM and the CSM employs a vertex-based FVM. For this reason the accuracy of the thermo-mechanical coupling is somewhat dependent upon the extrapolation technique employed to obtain the temperature field at the vertices from that at the cell centres. This can introduce inaccuracies in the vertex-based temperature field when the mesh is unstructured, fortunately the inaccuracies diminish as the mesh is refined.

8.2 Further research

The potential avenues for further research have been highlighted as they arose throughout the thesis. In this section a summary of the potential further research will be given.

8.2.1 Contact analysis

At present the solid mechanics facilities within PHYSICA are limited to small strain, quasi-static, non-linear material problems. Further research which has already been undertaken, is the inclusion of contact analysis within a FV framework. This is required for the complete simulation of the shape casting of metals and requires the coupling of elasto-visco-plastic material behaviour with regard to the casting and deformable/rigid or deformable/deformable contact between casting and mould, depending upon the material properties of the mould involved in that particular shape casting process.

A number of researchers have already included contact analysis when applying the FEM to shape casting problems [67, 12], but this is not the case with regard to the FVM and it is possible that subtle differences may occur, again depending on the nature of the problem and the order of the elements employed. On the other hand, as has often been the case when comparing the FVM and the FEM, the two different approaches may actually achieve the same goal.

8.2.2 Optimisation

Further research is required to optimise the non-linear solution approach with regard to the FV formulation of the CSM. This would involve employing implicit integration techniques with regard to time stepping and modified Newton-Raphson methods combined with alternative preconditioners and solvers.

8.2.3 Solid mechanics

A great deal of further research is possible with regard to the CSM. This research includes further comparison and validation of the FVM when compared to the FEM for rate dependent material non-linearity. Comparison of the FVM and the FEM for general two and three dimensional contact analysis. Further research can also include the investigation of the applicability of the FVM to forming problems involving large deformations within a Lagrangian reference frame.

8.2.4 Shape casting of metals

With regard to the solid mechanics, the inclusion of a robust contact algorithm is a priority. This will facilitate deformation of both the casting and mould and provide increased accuracy in the gap formation. Also, gravitational effects have to be included, possibly by including inertial terms in the governing equations.

The PHYSICA framework can be generally extended in a numbers of ways to facilitate the comprehensive simulation of the shape casting of metals. Firstly, the additional modelling of the residual convection after the filling of the mould and the heat transfer associated with the filling. Also, in addition to the effect of buoyancy driven recirculation, the effect of volume change during solidification and the potential porosity formation associated with this phenomenon. Finally, the transient nature of the free surface associated with the liquid phase, with particular regard to feeding mechanisms in complex castings.

Most importantly the PHYSICA framework requires further validation against experimental results. This can include comparisons with the large number of experimental castings performed in the VERICAST project [44] and other benchmark shape casting problems that are now becoming public domain [85]. Additionally, further collaboration with the aerospace and automotive industries is required, particularly with regard to investment casting foundries and precision casting. Indeed, collaboration is currently underway to compare results from the experimental analyses of investment casting with numerical results from PHYSICA.