Geometry Based Casting Solidification Simulation for Visualizing Feed-paths

First Stage Report

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Abstract

Designers can easily modify the design of castings to reduce potential manufacturing problems if the manufacturing incompatibility of a product can be evaluated at an early product design stage. This will reduce manufacturing problems, redesign, costs, and lead times while improving quality. Casting solidification simulation plays a vital role to ensure manufacturing compatibility for the casting process. Physics driven and geometry driven approaches for casting simulation have been explored by many researchers. Physics driven approaches are comprehensive but require more computation time, and have greater hardware requirements. On the other hand geometry driven approaches are fundamental and require less computational time but lack in taking into account the physics of thermal boundary conditions. A geometry driven, Gradient Vector Method (GVM) is implemented in this work, where a casting geometry is divided into a number of pyramidal segments and interfacial heat flux is computed for each segment. These heat flux vectors are a function of material properties, geometric parameters and thermal boundary conditions. The vector sum of these heat flux vectors indicates the direction and magnitude of the net interfacial flux or maximum temperature gradient. This method is iterative in nature and need marching along the direction of maximum temperature gradient by a finite step size to generate the feed metal path.

The model is capable to identify multiple hot spots and its results are compared with commercial finite element method based software for several test cases. Amongst geometric based methods, GVM is far more computationally efficient whilst maintaining sensitivity towards boundary conditions and material properties. Further work based upon GVM is discussed in the final chapter.

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Chapter 1

Introduction

Casting is a widely used manufacturing process to produce near net shape components. Casting can be used for parts of intricate shapes of a wide variety of materials. Over the past twenty years casting simulation has become an active area of research. Solidification simulation of castings plays an important role in assuring the soundness and quality of castings, in minimizing the trial production time and in reducing the manufacturing cost. Practical three dimensional computer numerical simulation system for temperature distribution during solidification as well as shrinkage cavity and porosity prediction has been put into application all over the world [1]. However simulation also has its own limitations. Simulation software is difficult to use for the common foundry man. Computational time in simulation can be as much as the foundry trials itself. In the following sections of this report, review of relevant literature on various casting simulation methods is presented. It is followed by statement of objectives, methodology and the plan for the proposed project. It is then followed by a three dimensional implementation of the geometry based Gradient Vector Method and results for simple three dimensional shapes which have then been compared with results of commercial FEM software.

1.1. Casting Solidification Simulation

Casting solidification simulation has been widely used to predict solidification related defects like shrinkage cavity, porosity, microstructure, residual stresses etc. Shrinkage cavity is a common defect in castings. As casting solidifies liquid-solid interface progressively moves from the mold boundary till it reaches to certain point/points in the mold-cavity; known as hot spot/spots, where interface disappears. During the process, metal contracts and subsequently to compensate this requirement, microscopically liquid metal flows from nearby hot region to solidifying region [2]. The path along which this microscopic metal flow occurs is known as *feed-path* [3].

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Many simulation methods are being used to predict the occurrence of shrinkage cavities. They include both physics based and geometry based methods. Physics driven methods observe the laws of conservation of mass, momentum, and energy to simulate the physical behaviour of solidification process. Based on continuum mechanics, governing partial differential equations are formulated, and solved numerically. Boundary conditions at metal-mold interface influence the solidification process and are incorporated by employing interfacial heat transfer coefficient (IHTC). The IHTC values can be modelled as function of casting temperature at interface [4], [5] or as function of air gap formation between mold and casting [6]. Alternatively, geometry driven methods provide a valuable insight of the solidification time of different regions of the casting and therefore indirectly indicate propensity for defect formation during solidification. Solidification front movement can be derived from solidification time and sequence data, which in turn is used to generate feed-paths. Computation time for geometric reasoning driven methods is very less, as compared to the highly computation intensive fluid flow, heat transfer and solidification kinetics models. Geometry based methods are computationally less intensive than physics based methods however they do not take into account complex physical phenomenon.

1.2. Shrinkage Defect Prediction

One of the most important purposes of solidification simulation is to predict and then to avoid shrinkage cavity and porosity if they will occur in shaped castings. Many works have been done for the purpose of predicting shrinkage cavity and porosity of castings and many prediction criteria or methods have been proposed as well, such as: (1) G, temperature gradient method, (2) $G/\sqrt{R}$, where R is solidification rate, [7] and (3) GF, critical solid fraction gradient method. Also a lot of experimental work were carried out to comprehend casting feeding behaviour during solidification and to evolve criteria for prediction of solidification related defects. Early experimental work on casting feeding was carried out by Naval Research Laboratory by for determining feeding distances [8-12] and adequate riser dimensions [12], [13]. Numerous rectangular sections and bar shaped castings were cast to evolve empirical relations for feeding distance. However for most practical applications most of them are used qualitatively instead of quantitatively [1]. Numerical simulation of solidification often has to rely on such prediction criteria to predict the occurrence of shrinkage defects. On the other hand much simpler geometry based methods can predict

shrinkage defects without using any empirical criterion. Such methods require a minimum of inputs and can predict defects based only on the geometry of the component. These methods avoid the requirement of inputs like interfacial heat transfer coefficient and material properties most of which are inaccessible to foundry men.

1.3. Organization of the Report

The present chapter provides an introduction to casting solidification simulation and its use to predict shrinkage defects in castings. In Chapter 2 the various methods used for casting solidification simulation are presented including physics based and geometry based methods. The problem definition, goal and research approach are specified in Chapter 3. An account of the preliminary work carried out is mentioned in Chapter 4 including the 3D implementation of the Gradient Vector Method and results for various three dimensional shapes and their comparison with FEM results of commercial software. The report concludes with a chapter on the summary of the work and plans of future work to be carried out.

Chapter 2

Literature Survey

Simulation methods are being actively used to predict defects in shaped castings. There exist a wide variety of simulation techniques with several variations that take into account different phenomenon occurring during the casting process. The following is a review of literature on the various simulation methods used for simulating solidification and their relative advantages and disadvantages.

2.1. Heat Transfer in Metal Casting

Heat is transferred by three basic mechanisms: conduction, convection and radiation. In the context of metal casting, conduction is the mechanism by which heat is transferred within the solidifying metal and the mold. Convection mode of heat transfer is considered in many contexts like

- Heat transferred within liquid metal
- Heat lost from outer surface of the mold
- Heat transferred at metal-mold interface
- Heating of gates during pouring
- Heat transferred during macro and micro-segregation.

Radiation mode of heat transferred includes heat lost from outer surface of the mold and at metal-mold interface when air gap formed. It also includes heat loss from open risers or feeders.

2.1.1. Governing equations

Energy equation in liquid phase of metal with temperature formulation: Temperature, T taken as field variable

$$\frac{\partial(\rho_l T_l)}{\partial t} + \nabla.(\rho_l u C_l T_l) = \nabla.\left(\frac{k_l}{C_l}\nabla T_l\right)$$

Energy equation in solid phase of metal with temperature formulation: Temperature, T taken as field variable

$$\frac{\partial(\rho_s T_s)}{\partial t} = \nabla.\left(\frac{k_s}{C_s}\nabla T_s\right)$$

Energy equation at solid-liquid moving interface, $S(t)$ with latent heat source term

$$k_s\frac{\partial T_s}{\partial x} - k_l\frac{\partial T_l}{\partial x} = \rho_s L\frac{dS(t)}{dt}$$

Energy equation with Enthalpy formulation: enthalpy, h taken as field variable [14]

$$\frac{\partial(\rho h)}{\partial t} + \nabla.(\rho v h) = \nabla.(\Gamma\nabla h) - \rho\frac{\partial(\Delta H)}{\partial t}$$

Where, $\Gamma = \dfrac{k_H}{C_H}$

The index H indicates the dependence of the specific heat and thermal conductivity on the enthalpy. Enthalpy formation implicitly takes care of the release of latent heat, as it includes whole area of solid and liquid phase. Hence, moving solid-liquid interface need not be considered.

2.2. Simulation – Physics Based

2.2.1. Finite Element Method

Finite element simulation of casting solidification process is an efficient way to analyse the process of solidification. It involves the physical approximation of the domain, wherein the given domain is divided into sub-domains called as elements. The field variable inside the elements is approximated using its value at nodes. Elemental matrices are obtained using Galerkin's weighted residual or variational principles and are assembled in the same way, as the elements constitute the domain. This process results in the set of simultaneous equations. The solution of these set of equations gives the field variables at the nodes of the elements

With FEM we can solve simultaneously energy equation with advection and diffusion term, momentum equation with advection, diffusion and buoyancy term and continuity equation.

Advantages of FEM:
- Ability to model complex domains
- Ability to handle non-linear boundaries
- The ease of implementing boundary conditions

Disadvantages of FEM:
- Method requires more effort for formulation of the problem and data preparation
- Needs long processing time
- Large memory space required.

2.2.2. Boundary Element Method

Boundary element formulation of a problem requires rewriting of the field equation as integral equations. Partial differential equations (PDEs) are transformed to the integral description of boundary effects, in the form of the boundary integral equations. This integral description leads to a formulation of the problem to a lower dimensional level. It means reduction of problem dimension by one, as boundary of any domain is of a dimension one less than that of the domain.

In BEM only the boundary needs to discretised. A direct consequence is that, substantially reduction in set of equations, containing fewer degrees of freedom. Therefore BEM requires less processing time and memory as compared to FEM

Solution methodology: Choose a trial function for field variable such that it,
- Satisfies the Domain (Governing PDEs) exactly.
- Satisfies the boundary conditions approximately.

Therefore in BEM the problem is moved from within the domain to its boundary. This means it maps the domain to the boundary (For e.g. Area to Line).

2.2.3. Finite Difference Method

For analysis of Finite difference methods we are primarily interested in stability and accuracy. Stability imposes conditions on the relation between time step and grid spacing which must hold to prevent uncontrolled growth of errors. The accuracy is a measure of how

well the discretization approximates the PDE and hence also at which rate the approximation converges to the exact solution as grid spacing and time step decrease.

In computation one would like to determine an approximate solution to a given tolerance as fast as possible. The stability and accuracy of numerical schemes have a crucial impact since they govern the range of time steps and grid spacing resulting in the desired accuracy. For explicit schemes the simulation time increases with the number of time steps taken, and the execution time per time step grows linearly with the number of grid points. This is not necessarily true for implicit schemes, when a system of equations must be solved each time step. The stability conditions for implicit schemes are however often much less restrictive.
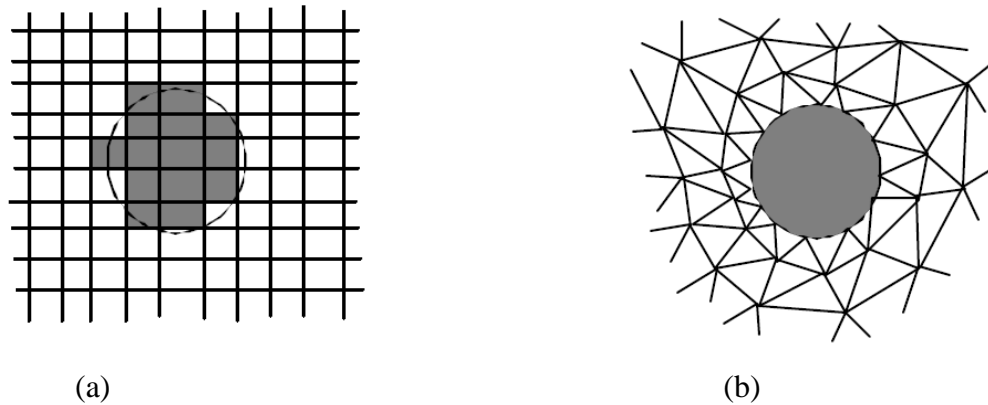

<div align="center">(a)   (b)</div>

Figure 2-1 Finite element and finite difference mesh resolution of circular object [15]

The FE method uses body fitted computational grids leading to more accurate representation of metal/mold interfaces than generally achievable by FD methods as shown in Fig 3.1. However, generating good quality FE grids is still a challenging task and often takes significantly more time than the simulation itself. Solution accuracy degenerates in highly distorted grids and changes in geometry, even small ones, often require a completely new grid.

2.2.4. Finite Volume Method

Finite volume method involves the integration of governing differential equation over a control volume (CV). Gauss divergence theorem is then used to convert the volume integrals into surface integrals in 3D (surface integral to line integrals in 2D and line integrals to simple differences in 1D) representing convection and diffusive fluxes across the individual CV faces. By doing spatial integration over CV, finite volume methods are fundamentally

dealing with evolution of cell average values of a scalar (Temperature, pressure etc.), rather than nodal point values.

FVM is much easier than FEM to understand and implement. But the most obvious advantage of FEM is the more general and mathematically consistent approach, which results in high flexibility. For example it is possible to construct a shape function that takes into account the analytical solution of the problem, so that only a small number of finite elements are required to resolve a complex phenomenon [16].

2.3. Simulation – Geometry Based

Alternatively, geometry driven methods provide a valuable insight of the solidification time of different regions of the casting and therefore indirectly indicates propensity for defect formation during solidification. Solidification front movement can be derived from solidification time and sequence data, which in turn used to generate feed-paths. Computation time for geometric reasoning driven methods is very less, as compared to the highly computation intensive fluid flow, heat transfer and solidification kinetics models. Researcher used it as a tool to arrive at first approximate solutions and subsequently minimizing the number of runs of the comprehensive models [2].

The conventional Heuvers' circle method [17], [18] based on the geometric modulus principle is an example of implementing simple geometric reasoning for predicting solidification related defects. The method consists of inscribing a series of circles, the diameter of which increases progressively in the direction of the feeder head to facilitate directional solidification and complete feeding. Chorinov in 1940 proposed a relationship between solidification time and section modulus for sand casting process where major resistance to heat flow is offered by mold. This is easy to calculate for simple shapes but for complex shapes it is difficult to divide the part geometry into separate identifiable sections. [19] investigated a new approach to calculate section modulus by using the concept of distance from the mold in cooling directions. [20] further normalised this concept by introducing normalizing factor. Several attempts have been made to use Chorinov's rule to describe sequence of solidification. This relation works best for geometries for which no part of the mold material becomes saturated with heat. Thus it does not apply to internal corners or internal cores. [21] have extended the concept the three dimensions for angular sections, plate

sections and to capture end effects. HCM has invited criticism because all padding additions have to be removed using expensive dressing operations, and like other geometric methods, it remains a qualitative analysis that is insensitive to material properties and boundary conditions.

2.3.1. Vector Element Method

An alternative approach to solidification simulation is by Vector Element Method [22]. In this method rays are projected from a given point inside the casting in all directions and their intersections with the section boundary are recorded and resultant of vectors along these rays point towards the hot spot. Later this work was extended to three dimensional models and a better approach to compute vector length in terms of modulus was introduced along with computation of feed-paths [3]. The casting section is divided into a number of pyramidal segments each subtending the same segment angle at a point inside the casting. Modulus vector for each segment is defined as

$$g = \frac{3\beta}{2\pi}\frac{V}{A}$$

Where V is volume of the pyramidal segment, β is solid angle of the pyramidal segment, and A is the area of its base. VEM is quick and accurate in predicting hot spots. It is capable of computing multiple hot spots if present. On account of less simulation time required, VEM is used for design and optimization of feeding system [23] for development of quality castings with a shorter lead time. Later, [24] applied VEM for design and classification of 3D junctions in castings. Modulus dependency of VEM makes feed-paths at geometric boundary more directed towards hot spot; in contrast ideally feed-paths are normal at the geometric boundaries.

2.4. Summary of Literature Review

1. Simulation techniques are being widely used to predict shrinkage defects in castings.
2. Physics based methods are comprehensive and take into account various physical phenomenon and boundary conditions. They are highly computationally intensive.
3. Geometry based phenomenon depend only on part geometry and are computationally efficient.
4. Finite element techniques (FEM) are the more general and mathematically consistent approach, which results in high flexibility. They can handle complex geometry and boundary conditions are easy to implement using FEM.

5. Finite difference techniques (FDM) are conceptually simple and easy to realize and are most widely used by the researchers.

6. Boundary element techniques (BEM) require only the boundary to be discretized. They take less time and less memory of the computational system

7. Finite volume techniques (FVM) involve the integration of governing differential equation over a control volume (CV). FVM are more accurate representation of the continuum mechanics problems, and recently it finds attention of many researchers.

8. The vector element method divides the geometry in pyramidal segments and uses modulus vector to generate feed-paths.

Chapter 3

Problem Definition

3.1. Motivation

In the casting of metals, the phenomenon of solidification plays an important and decisive role in determining the quality of cast components. Castings are widely used in many industrial sectors and employ processes that are gravity (e.g., die, sand, and investment) or pressure based. In all cases, the goal is the production process of near net shaped components. However, the casting process is not clean and reliable; there are lots of parameters that affect the final product quantitatively and qualitatively. Solidification simulation helps in providing more reliable

Shrinkage defect is the major cause of rejection in the majority of castings. Over the years many researchers have used various numerical methods to predict the occurrence of shrinkage in castings. These include both physics based and geometry based approaches. Physics based systems are comprehensive i.e. able to capture the effects of a wide variety of physical phenomena however they are computationally intensive and require large amounts of memory. This limits the number of trials that can be conducted with simulation programs. Also physics based simulations require a large number of inputs some of which like heat transfer coefficients are difficult to obtain for the common foundry man. Geometry based simulation on the other hand requires little other input besides the part geometry itself. Such methods can sometimes be orders of magnitude faster than physics based methods.

3.2. Goal

"Develop a geometry based method for the prediction of shrinkage cavities due to hotspots in castings while taking into account various boundary conditions due to use of feed aids like chills and insulation sleeves"

3.3. Research Objectives

A. Prediction of shrinkage in castings using a geometry driven model to carry out casting simulation.

B. Implementation of the Geometry driven model and its use to find the location of hotspots and hence shrinkage defects.

C. Extend the model so that it can be used with various feed aids like sleeves, covers, chills and fins which are common practice in the foundry industry.

3.4. Research Approach

3.4.1. Geometry based simulation

Gradient Vector Method (GVM) is a geometry driven approach based on heat flux vectors which is used for prediction of location of shrinkage defects. GVM is based on the principle that the highest temperature gradient at any point on the solid-liquid interface is normal to the interface. Casting geometry is divided into a number of pyramidal sections from an observation point and interfacial heat flux vector is computed for each geometric segment. Heat flux vector is the function of casting geometry, material properties and boundary conditions. Vector sum of these heat flux vectors indicates the magnitude and direction of the net interfacial heat flux. A mass less particle is used to continuously track the movement of the interface. The locus of points along which the mass-less particle moves represents the feed-path in reverse.

3.4.2. Implementation

The method will be implemented in three dimensions using Microsoft Visual C# and WPF. The program will be capable of opening a file containing voxel information of a part. It will then use GVM to calculate and display feed metal paths for the part. To generate the feed-paths the program will divide the geometry into pyramidal segments. It will calculate the heat flux vector in each segment. The resultant of these vectors is the feed-path in reverse. The program then moves a mass less particle along the feed-path for a finite distance. It then repeats the procedure of dividing the geometry into segments. This iterative procedure will be employed to obtain feed-paths.

3.4.3. Validation

The results of the Gradient Vector Method will be assessed on several test cases undergoing solidification. Test cases having various geometries: square, L shaped, Stepped, C shaped and T shaped domains will be compared with results of commercial FEM software ProCAST carried out by [25].

Chapter 4

Preliminary Work

4.1. 3D Implementation of Gradient Vector Method

4.1.1. Gradient Vector Method

Gradient Vector Method (GVM), a novel geometry-driven thermal model is used to compute interfacial heat flux during casting solidification. The extended model is used for computation of feed-path and hot spot by continuously tracking the liquid-solid interface. It responds well to cast metal properties, thermal boundary conditions and part geometry.

Gradient Vector Method (GVM) proposed by [2] is based on the principle that the direction of the highest temperature gradient at any point on liquid-solid interface contour is normal to that contour. Consider a Control Volume (CV) as shown Figure 4-1, liquid-solid interface is passing through two observation point P and Q. Interfacial heat flux q_P and q_Q due to latent heat evolution is shown at point P and Q, respectively. Interfacial heat flux is directed normal to the liquid-solid interface as shown by dashed arrows. Interface propagates in opposite direction to interfacial heat flux as shown by solid arrows. Nature of heat flow at any point on interface can be divergent, convergent or parallel, depends upon the geometry of the part. In this case shown in Figure 4-1, it is divergent. Feed-path is computed by continuously tracking the direction of the interfacial heat flux, as feeding occurs in the direction of maximum temperature gradient, from highest to lowest temperature.
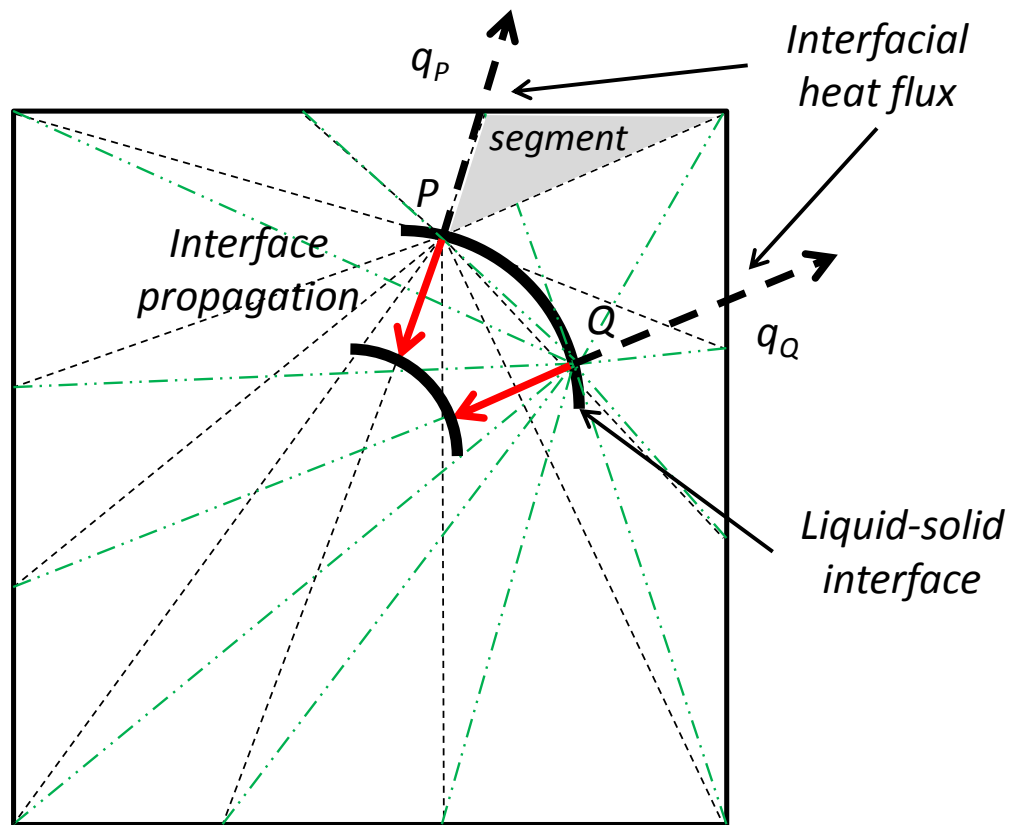
Figure 4-1Control volume with geometric and thermal parameters [2]

The CV is divided into a number of small pyramidal segments from the observation point, as shown in Figure 4-1, interfacial heat flux for each segment is calculated considering observation point is at liquid-solid interface. Solidification of each segment starts from boundary exposed to the mold and continues till it reaches the observation point. Interfacial heat flux for each segment is computed by deriving analytical solution to heat transport. Non-divergent nature of heat flow is assumed for each segment, which needs heat flux to be directed towards centre of gravity of segment. The methodology is illustrated with square casting as shown in Figure 4-2a. Solid lines indicates liquid-solid interface contours evolved over time as solidification progresses. Let us consider a point P_i on a liquid-solid interface contour and divide the geometry with equal segment angle, β. In present case segment angle is 45°, and number of segments is eight. Compute head flux for each segment. The same is plotted with thin arrows. Net heat flux at interface is derived by taking vector sum of the segmental heat flux as shown by thick dashed arrow in Figure 4-2a and Figure 4-2b. Net heat flow can be divergent, non-divergent or convergent, depending upon part geometry and thermal boundary conditions.

Net interfacial heat flux $\vec{q}_{net} = \sum_{s=1}^{s=n} q_{is}$

Where, *n* is number of segment and q_{is} is segmental heat flux
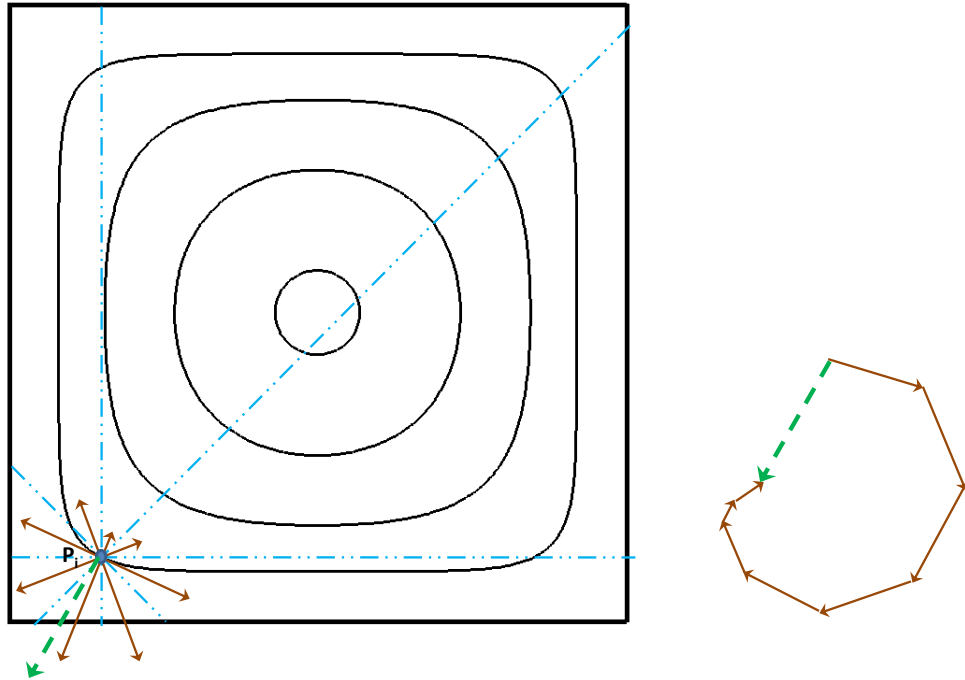

Figure 4-2 Computation of segmental heat flux, and Vector sum of segmental heat flux [2]

The accuracy of the model depends upon number and size of segment. Smaller the size, higher the accuracy.

In sand casting major resistance to heat transfer is offered by mold as compared to metal-mold interface and solidified metal itself. Figure 4-3 illustrates the heat transfer mechanism in this situation. Major temperature gradient exists in mold, whereas temperature gradient in metal can be neglected.

The interfacial heat flux of segment *s* is given by

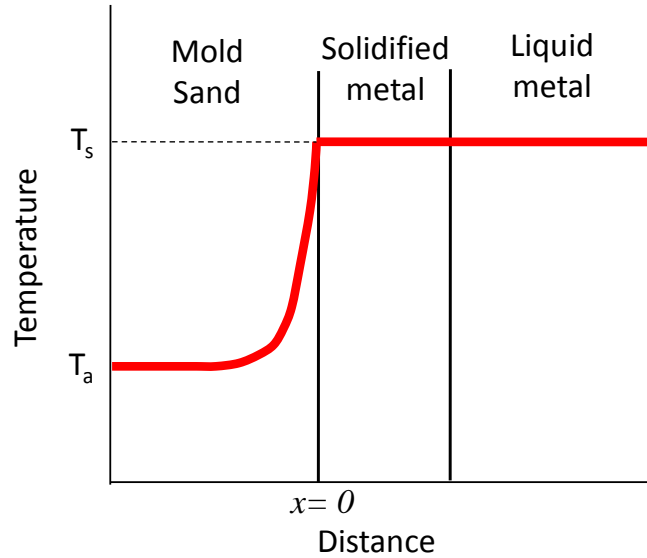$$q_{is} = -\frac{4}{\pi} \frac{(T_s - T_a)^2}{\rho_s \Delta H_l} \frac{k_m \rho_m C_m}{L_{cs}}$$

Figure 4-3 Heat transfer in sand casting process [2]

Feed-path and Hot Spot Computation Model

Feed-path is computed by continuously tracking the movement of the interface in opposite direction, as feeding occurs in the direction of maximum temperature gradient, from highest to lowest temperature. Convergence point of feed-paths indicates hot spot. The method is capable of identifying multiple hot spots, if present. The methodology is illustrated with square casting as shown in Figure 4-4. Let us consider a mass-less particle at position P_i on initial liquid-solid interface contour and compute the direction of net interfacial heat flux by dividing the geometry into a number of small segments. Direction of net interfacial heat flux is indicated by dotted arrow in Figure 4-4.

March the mass-less particle opposite to the net interfacial heat flux direction to move a small step towards hot spot as shown by thin arrows in Figure 4-4. New position of mass-less particle is computed as

$$P_{i+1} = P_i - \vec{U}_q \Delta s$$

Where, $\vec{U}_q$ is the unit vector in the direction of thye net interfacial heat flux and Δs step size for marching.

Repeat the same procedure at point P_{i+1} and continue till it reaches region where net interfacial heat flux is negligible or almost zero. This last point P_{i+n} corresponds to the point

of local maxima of temperature and where temperature gradient tends to zero represents the local hot spot.

Locus of the points along which mass-less particle moves from P_i to P_{i+n} represents the trace of the feed-path. During solidification when temperature T_i of the molten metal at point P_i reaches the solidus temperature, feed metal to compensate solidification shrinkage is supplied from point P_{i+1} as it is having highest temperature gradient towards point P_i. Therefore feeding occurs in opposite direction to the mass-less particle movement *i.e* from point P_{i+n} to P_i as shown by thick solid arrow in Figure 4-4
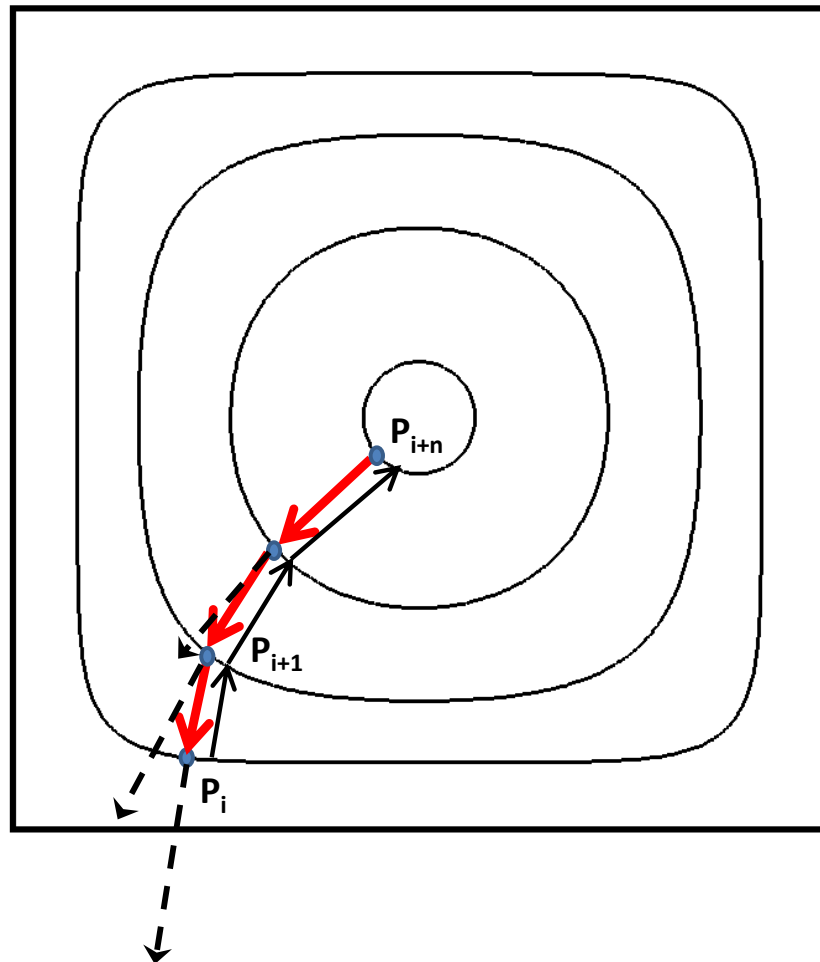

Figure 4-4 Feed-path computation [2]

Multiple hot spots, if any present, can be discovered by computing feed-paths from several seed points. Method is iterative in nature and accuracy of feed-path depends upon time step size and number of segments. The GVM does not involve the complexities of other

numerical methods yet provides robust and reliable results. The geometrically implicit nature of GVM ensures convergence of results after each iteration, allowing the choice of a larger step size, making it a speedy and robust model. This is not the case for physics-driven methods which rely heavily on material properties. In physics-driven methods onus is on users to ensure convergence and accuracy of result by ensuring correct material properties of cast metal, mold and feed-aid materials.

4.2. 3D Implementation in C#

The program is implemented in Microsoft Visual C# and WPF. The program can read information from a voxel file which has a voxel model of a given part. The voxel model is then triangulated for display purposes and displayed in 3D using the WPF 3D library. The program uses various structures to reduce complexity and improve code readability.

The structures used in the program are as follows:

Point3D: This is a structure provided by the WPF library. It represents a point in three dimensions with an X, Y and Z co-ordinate.

Vector3D: This structure is also provided by the WPF library which represents a vector in three dimensions with its magnitudes in the X, Y and Z direction respectively.

The WPF library provides many functions for these structures to carry out common operations like finding vector lengths, normalizing the vector etc.

Triangle:

The triangle structure is defined such that it contains three Point3D structures defining the three points constituting the triangle.
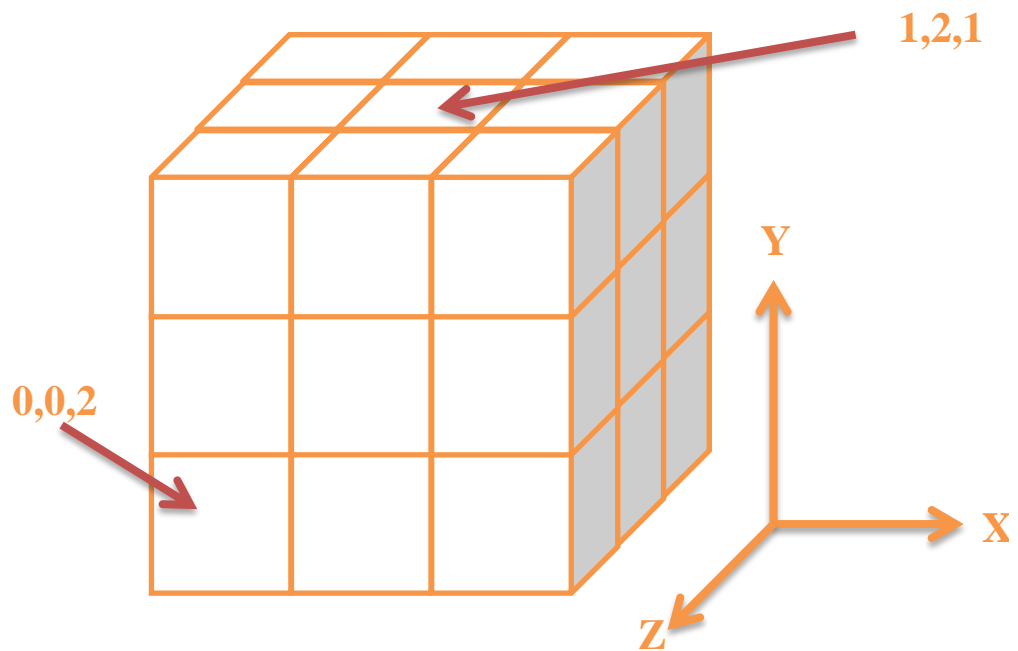
Figure 4-5 Index of a Voxel

Index:

The index structure consists of three integers i, j and k. This structure is used to denote the voxel number in the x, y and z directions respectively. *Figure 4-5* shows how the index of a voxel is determined. The index of the voxel is zero based i.e. the first voxel will have value zero.

Voxel:

The voxel structure contains a integer variable called fillStatus. The value 1 assigned to this variable is used to denote metal whereas 0 indicated mold material. This structure can be later extended to take into account core material, insulation, chills etc. if needed.

The classes used in the program are as follows:

VoxelModel:

This class contains a three dimensional array of voxels. This represents the part geometry. The class provides methods for the display of the model in three dimensions. The class has also been provided with methods that can return the co-ordinates of the voxel centre by taking the voxel index as the input or vice versa.

GVMFeedpaths:

This class contains methods that are used in the computation of feed-paths. The class contains the method that can open a text file that contains voxel information as input and stores the data in an object of type VoxelModel. It contains the IntersectionPointsMatrix and IntersectionPoint methods as well as methods to find the volume and base area of a pyramid.

4.2.1. Feed-path Computation

The program calculates feed-paths as follows:

The feed-path is denoted as an array of points. The calculation starts with an initial point. The routine NextFeedPoint generates the next feed point in the feed-path. The feed points are calculated successively and stored in the feed-path array. From the initial point the geometry is divided into tetrahedrons. The edges of these tetrahedrons extend up to the part surface. The characteristic length is computed as the volume divided by cooling surface area of the tetrahedral segment. This is then used to compute the heat flux vector. The resultant of the heat flux vectors is computed and it is then normalized to a fixed step size. The next feed point is found by moving the initial point in the direction of the resultant vector by the step size.

NextFeedPoint Routine:

This routine calculates the next feed point located on the feed-path using the current feed point. This routine uses a 3D matrix of points called IntersectionPointMatrix which stores the point of intersection of the intersection rays with the part geometry.

Division of Geometry into Tetrahedrons

Consider a cube which is divided into an equal number of smaller cubes. The number of divisions in one direction is stored in a variable called noOfSegments. For example if the noOfSegments is 3 then the cube is divided into 3x3x3 smaller cubes as shown in *Figure 4-6*. It is assumed that the centre of the larger cube is the initial point from which the next feed path needs to be computed. Every point of the cube is denoted by a zero based i, j and k which denote the position of the point in the x, y and z directions.
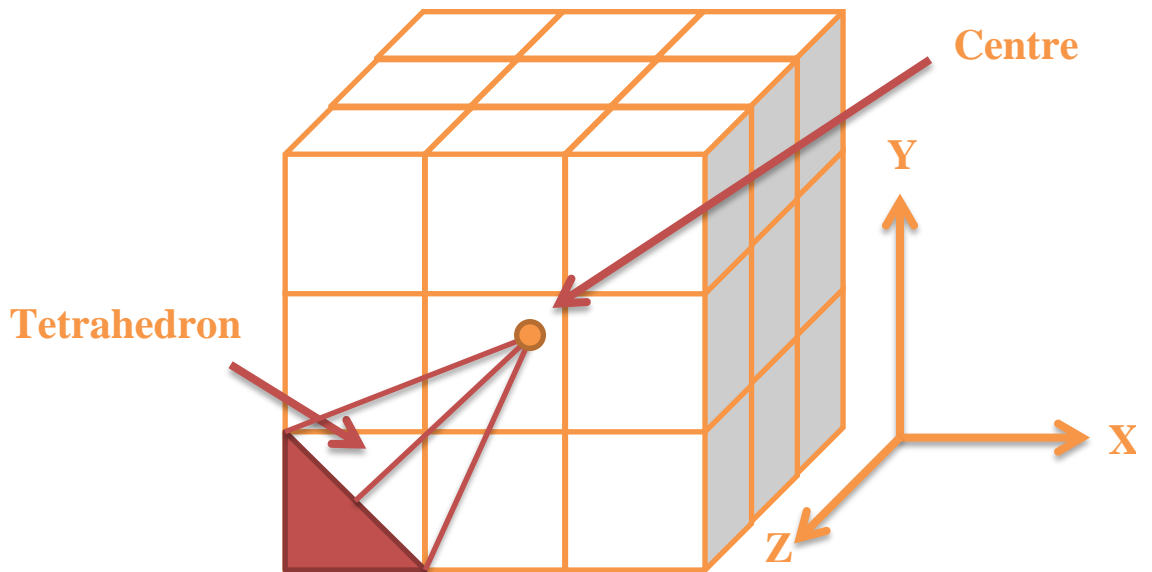
Figure 4-6 Division of Geometry

Each square face of each of the smaller cubes is divided into two triangles. The edges of the tetrahedrons pass through the vertices of the triangles and extend up to the part surface and its apex is the centre of the larger cube.

Intersection Point Matrix

The intersection point matrix is a 3D matrix of points which denote the intersection points of the intersection rays with the part geometry. This matrix is built using the IntersectionPoint routine required the cube center and the intersection vectors as input. The intersection vectors are vectors that point from the cube centre to each of the vertices of the external faces of the smaller cubes.

IntersectionPoint Routine

This routine computes the intersection point of a vector with the part geometry taking the vector and the source point as input. This is done as follows:

The source point is moved in the direction of the vector by a fixed distance while checking whether the voxel within which it lies belongs to metal. When this is not the case the surface voxel is reached and the step size is reduced to one tenth and the procedure is repeated till the step size reduces to a very small distance. This means that the point is a very close approximation to the point of intersection of the vector and the part geometry. This point is

then stored as an intersection point in the IntersectionPointMatrix at the corresponding location.

4.2.2. Solution Algorithm

The following is the algorithm used for the generation of feed-paths:

1. First the point from which the feed-path is to be calculated is determined.
2. The geometry is divided into tetrahedrons with the point as the apex.
3. The edges of these tetrahedrons are stored in a three dimensional matrix.
4. The intersection points of these edges with the geometry are found and are stored in another three dimensional matrix.
5. For each tetrahedron the corresponding intersection points are retrieved from the three dimensional matrix of intersection points.
6. Using these three points and the initial point as the apex the volume and area of the tetrahedron is computed.
7. Using this, the characteristic length Ls is computed for each tetrahedral segment which is equal to Volume/Area.
8. Now using this characteristic length and the equation $q_{is} = -\frac{4}{\pi} \frac{(T_s - T_a)^2}{\rho_s \Delta H_l} \frac{k_m \rho_m C_m}{L_{cs}}$ the heat flux vector magnitude is computed. The vector direction is taken as the centroid of the base.
9. The resultant of all these vectors is computed. This is the resultant heat flux vector.
10. If magnitude of net heat flux vector tends to zero

    Declare the point as hot spot

    Else,

    March the mass-less particle by a small step Δs in the opposite direction to the net interfacial heat flux, point P_{i+1}

    Repeat steps *2* to *7*
11. Steps 1 to 10 are repeated for the next feed point.

4.3. Results for various shapes

The gradient vector method was implemented in three dimensions in Microsoft Visual C# and WPF. The program uses a voxel file as input and generates feed-paths for the model.

The shapes for which the feed-paths were generated are shown below. The feed-path results of the shape have been compared with FEM results conducted in ProCAST software for the same shapes by [25]. The process parameters are as follows:

Metal: Pure Al   Mould: Sand Silica   Initial Temp: 660 $^{\circ}$C
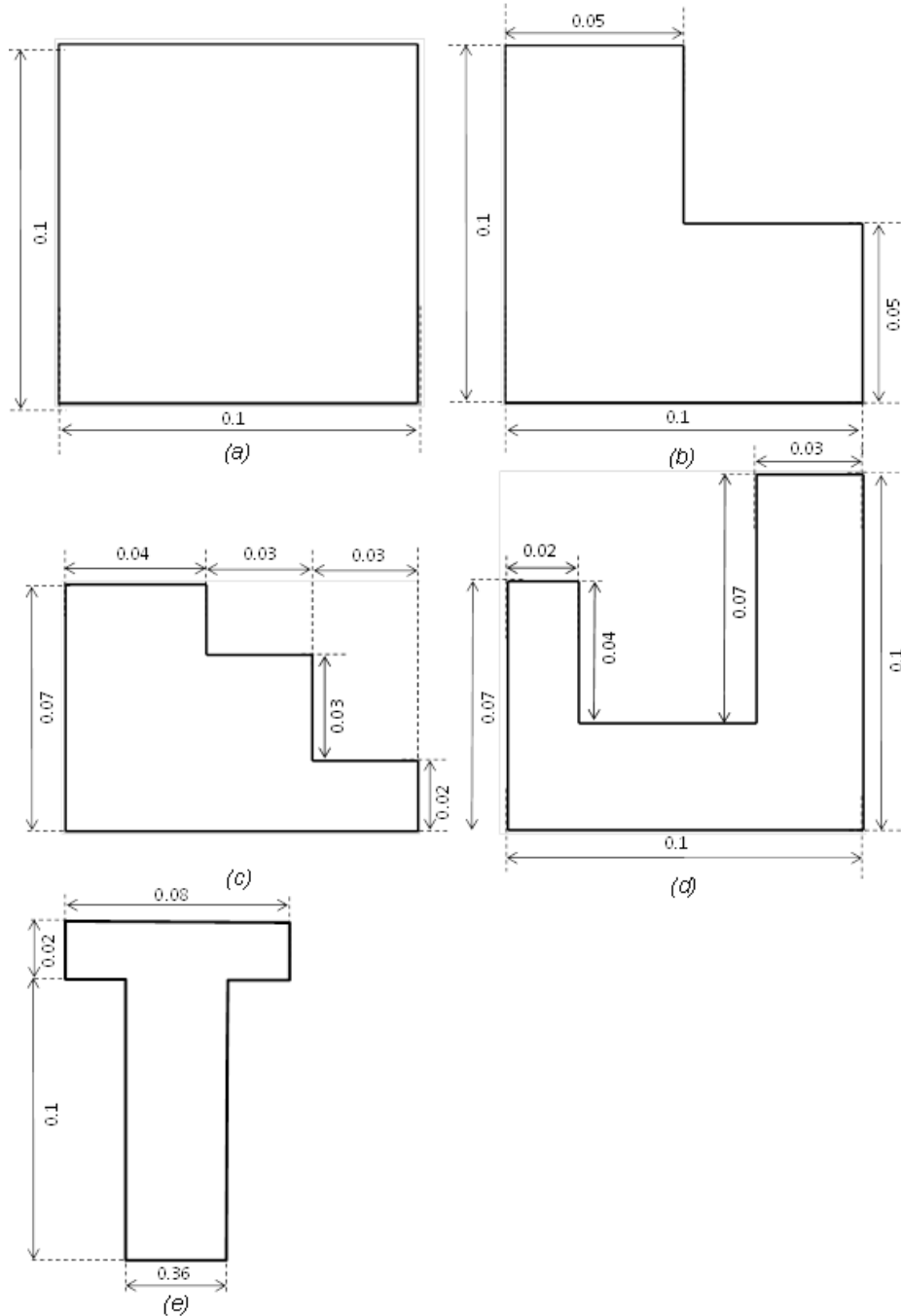
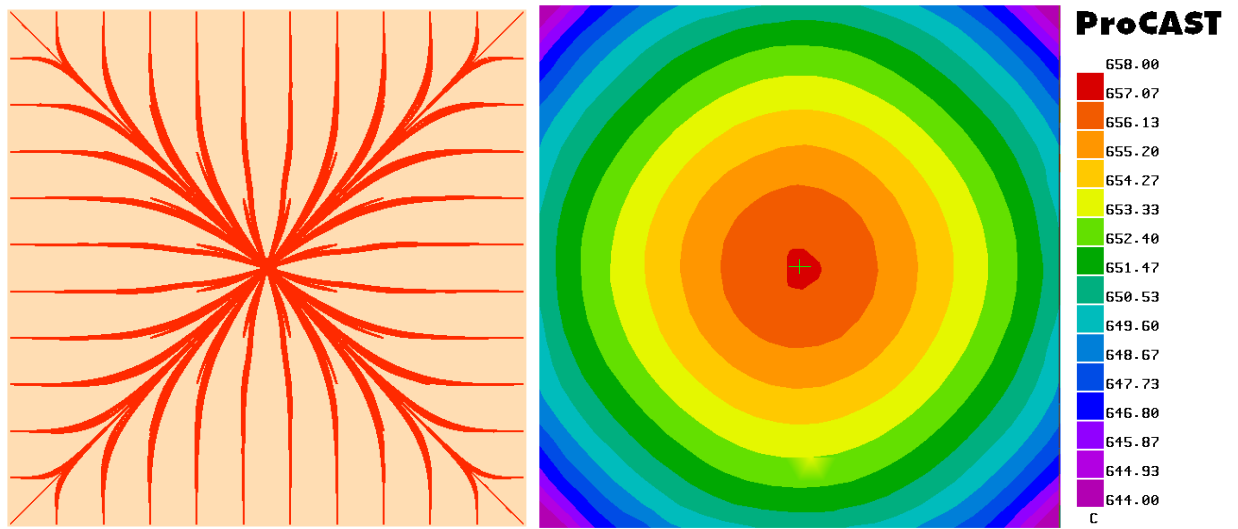IHTC: 100 W/m^2-K   Initial mould temperature: 30 $^{\circ}$C
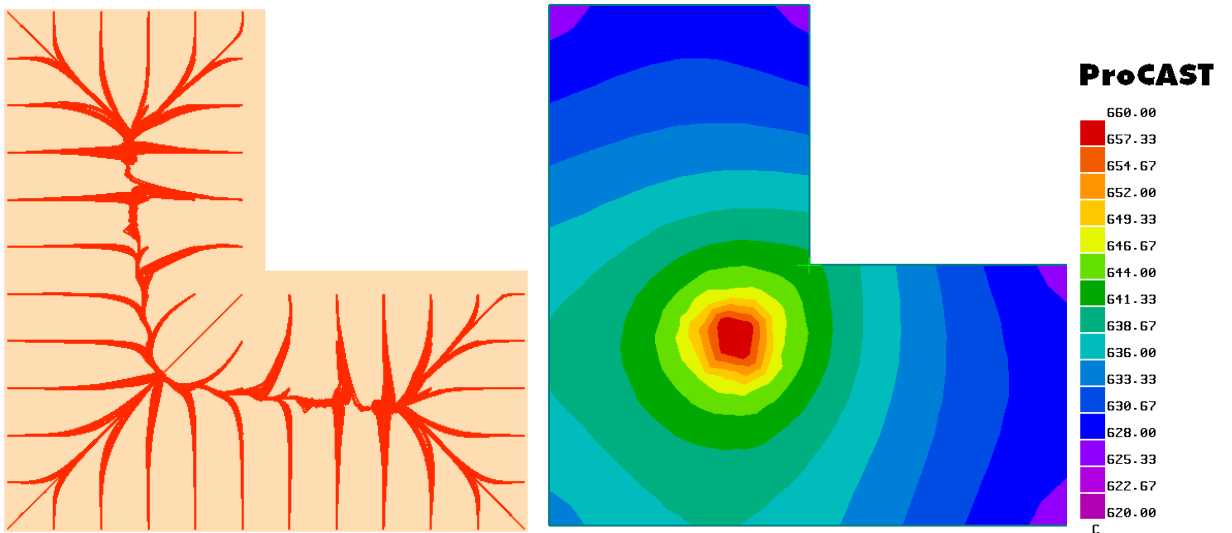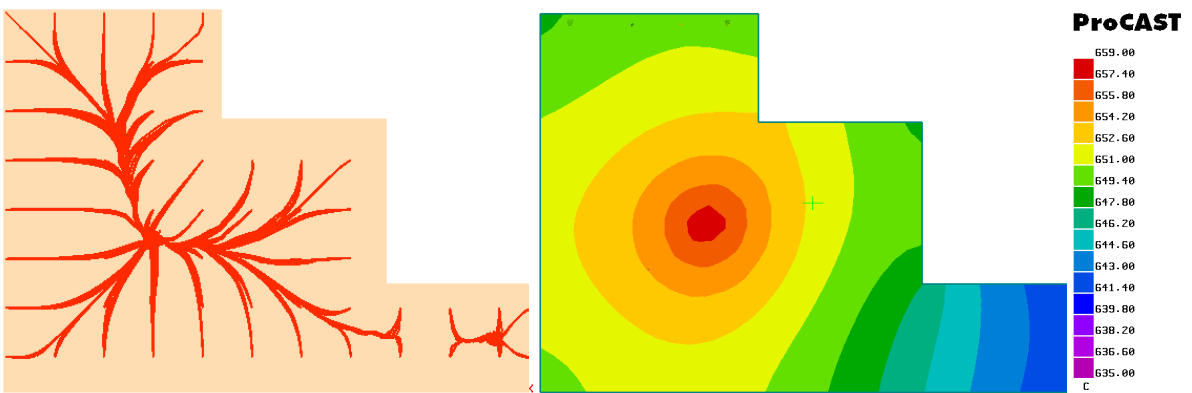

Figure 4-7 Computational domain (a) Square, (b) L shaped, (c) Stepped,
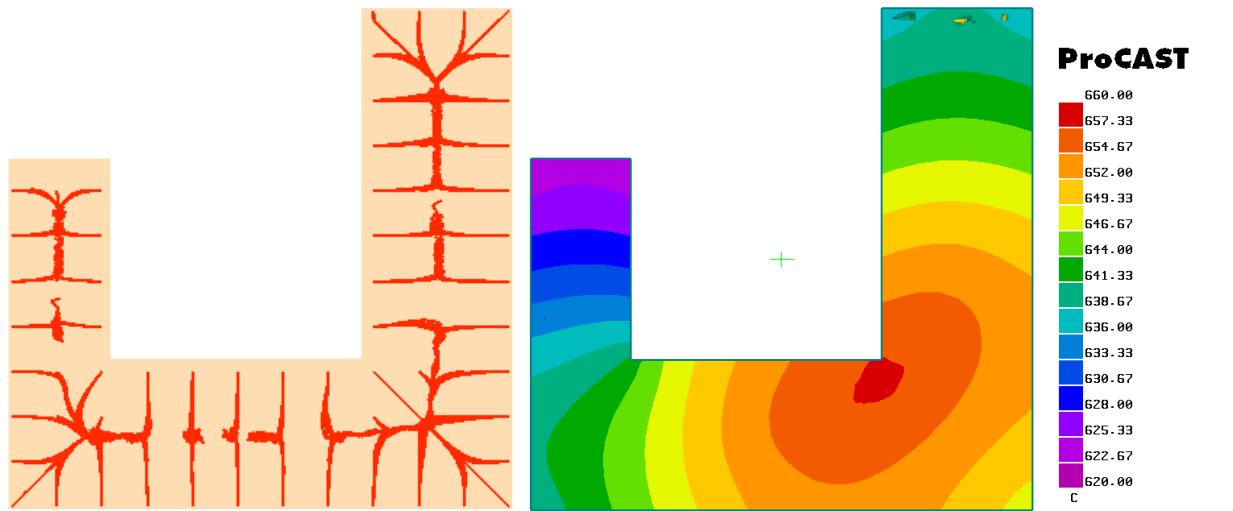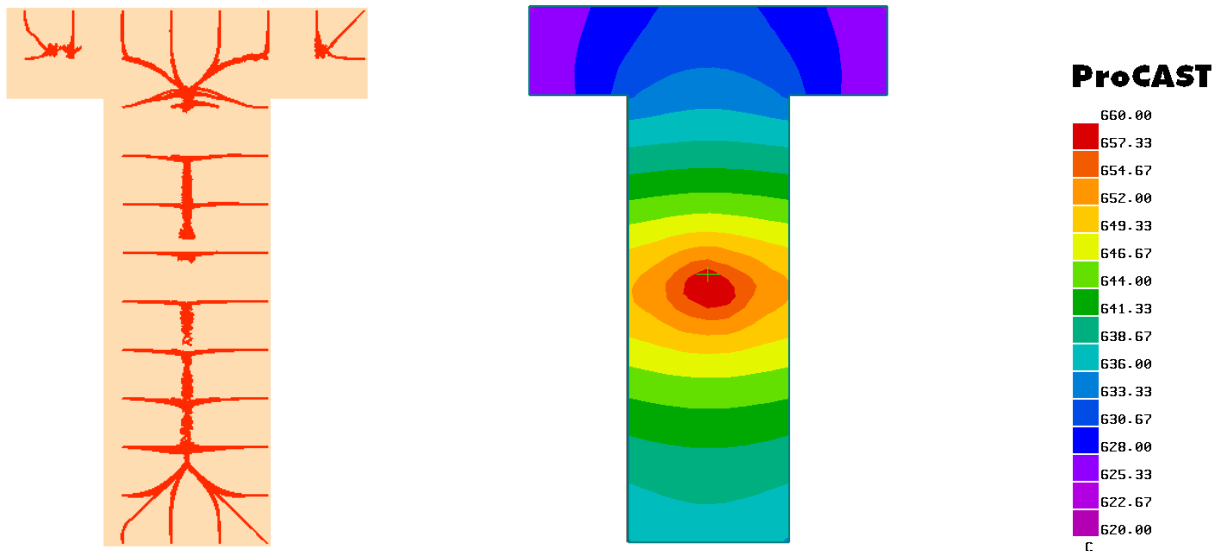*(d) C shaped and (e) T shaped domains with thickness 0.1m*

(a)

(b)

(c)

Figure 4-8 GVM feed-paths and FEM temperature contours for (a) Cube,

(b) L shaped, (c) Stepped domain

(d)

(e)

Figure 4-9 GVM feed-paths and FEM temperature contours for (d) C shaped and (e) T shaped domain
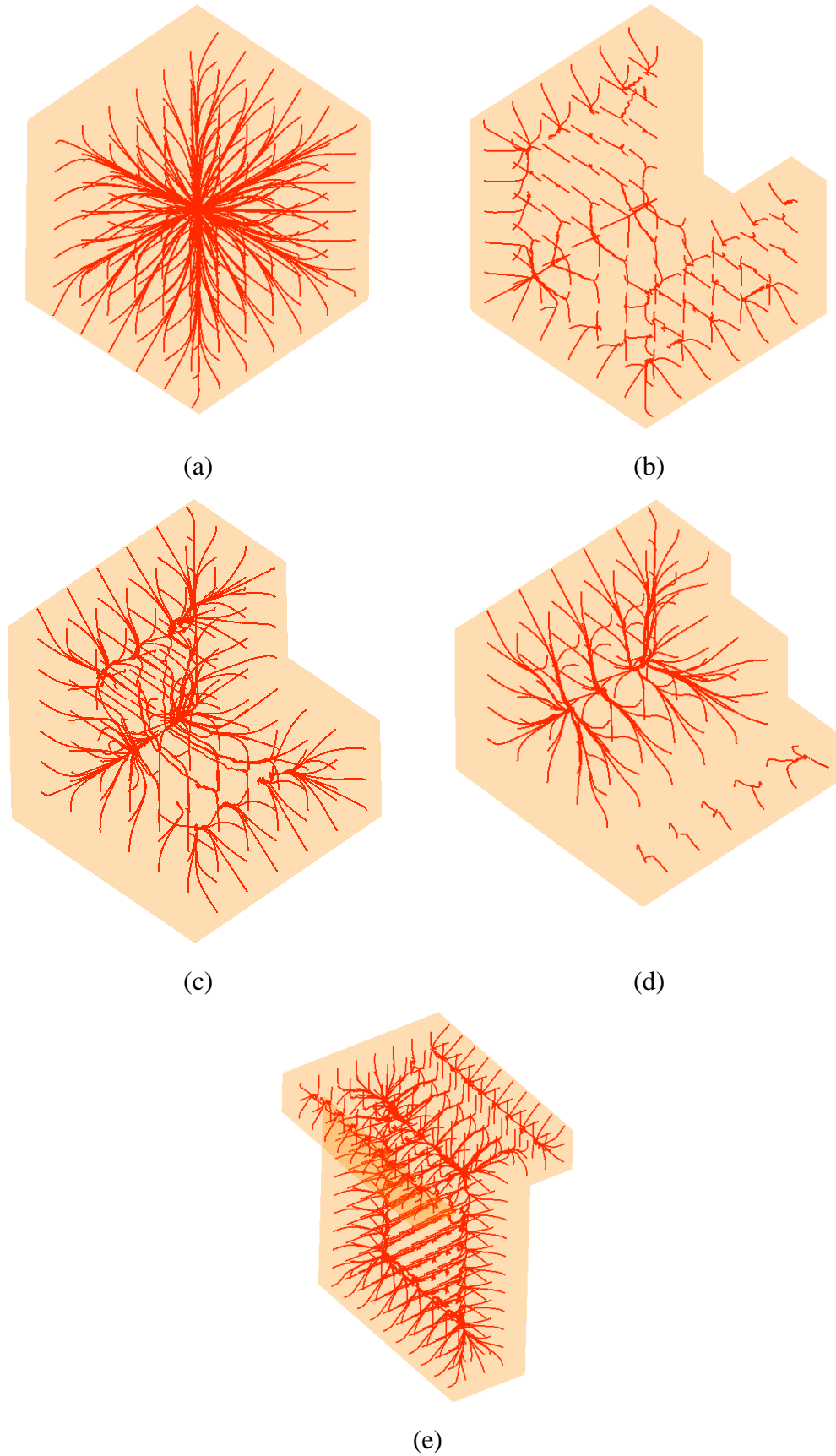
(a)

(b)

(c)

(d)

(e)

Figure 4-10 Three dimensional view of GVM feed-paths for (a) Cube, (b) L shaped, (c) Stepped, (d) C shaped and (e) T shaped domains

Chapter 5

Summary and Future Work

5.1. Conclusion

Simulation time and accuracy is a major concern for the foundry industry when a new product is under development. The most common cause of rejection in castings is shrinkage which occurs as the hot spot feeds liquid metal to the surrounding metal which is contracting. The Gradient Vector Method is an easy and computationally efficient method which can predict the location of hotspots in castings by calculating feed metal paths. In the present work GVM was used to compute feed metal paths for three dimensional castings of various shapes. The results were compared with results of commercial FEM software. GVM implicitly depends upon geometric and boundary conditions and explicitly depends upon material parameters, making it robust and computationally efficient.

5.2. Future Work

The following work is proposed for the future:

A. Further development of the Gradient Vector Method to handle various thermal boundary conditions accurately

B. Estimating the size and location of shrinkage cavity using feed-path results of Gradient Vector Method

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