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A Network Technique for Analysis of the Thermal Transient Casting Process

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ABSTRAK

Pendekatan rangkaian untuk mensimulasi terma dalam proses penuangan telah dibentangkan dibandingkan dengan data eksperimen dan model unsur terhingga. Untuk rangkaian tersebut, semua hasil perbandingan adalah baik dan memuaskan. Pendekatan ini adalah menjimatkan di segi penggunaan komputer (masa dapat dikurangkan) dan berpotensi untuk kerja-kerja reka bentuk pertama dalam acuan. Model yang dibentangkan juga berupaya untuk membuat beberapa kitaran penuangan di mana ianya dapat menunjukkan sejarah terma untuk mencapai operasi yang stabil.

ABSTRACT

A network approach to simulating the thermal transient casting process is presented and compared with experimental data and a continuum finite element model. For a sufficiently fine network, all comparisons are good. The approach is economical on computer effort and may be used for a first iteration in die design. The capability to model successive casting cycles is presented, which shows the die thermal history to achieve stable operation.

Keywords: network, thermal, finite, element, casting

INTRODUCTION

There are a number of numerical techniques which may be used to simulate the cooling and solidification of cast components. The finite difference approach (Phelke 1976) was used initially and is ideally suited to regular shapes which may be mapped by triangular, cylindrical or spherical coordinate systems. The finite element approach (Zienkeewicz 1977) overcomes this limitation by allowing the mesh generated to map the curved and often complex contours of the cast component in its die.

However, it is generally more complex then the finite difference scheme in calculation and usually requires a more significant computing effort to complete. This has led to an investigation into the use of boundary element method (Davey and Hinduja 1990) to simulate the casting, cooling and solidification process. The method retains the ability to map complex surfaces with the added advantage of reduced computational effort. However, since casting modelling requires the phase change process to be modelled accurately internal to the domain, this restricts the accuracy of the boundary element approach for solving this type of problem.

The lumped parameter (or network) analysis (Smith and Griffiths 1988) is a derivative of the finite element method. Effectively it is a beam element formulation and since the element stiffness matrices can be assembled directly without numerical integration it provides a potentially computationally economic route for analysing the casting process; this will be explained later in the paper.

In simulating the casting process, the numerical modelling tool must feature a number of capabilities, including

1) the ability to deal with different and nonlinear material properties
2) the capability to model heat transfer at either internal or external surfaces and to account for thermal interface effects between the cast part and its mould.
3) the ability to map complex shapes.

These features have been embodied into a continuum finite element model (Lewis and Roberts 1987) which has been configured into the format of a design tool for direct application in the foundry (Gethin *et al.* 1989, 1990). However, experience has shown that for typical cast parts, a two-dimensional analysis on a slice through the part and die can be time consuming to complete. Thus the network analysis may be used to establish a basic design prior to refined analysis using the finite element approach. This is particularly important where three-dimensional analysis is to be considered.

MATHEMATICAL BASIS

In any transient casting heat transfer analysis, there is heat transfer by conduction and there is a temporal depletion of energy from the molten metal to cause its solidification. This physics must be embodied into the mathematical basis for the process. *Fig. 1a* illustrates a section through a region of a cast part which has been divided into cells with nodes at the centre which are connected by conduction links to form a network structure. The heat flow through the single homogeneous link (*Fig. 1b*) is given by

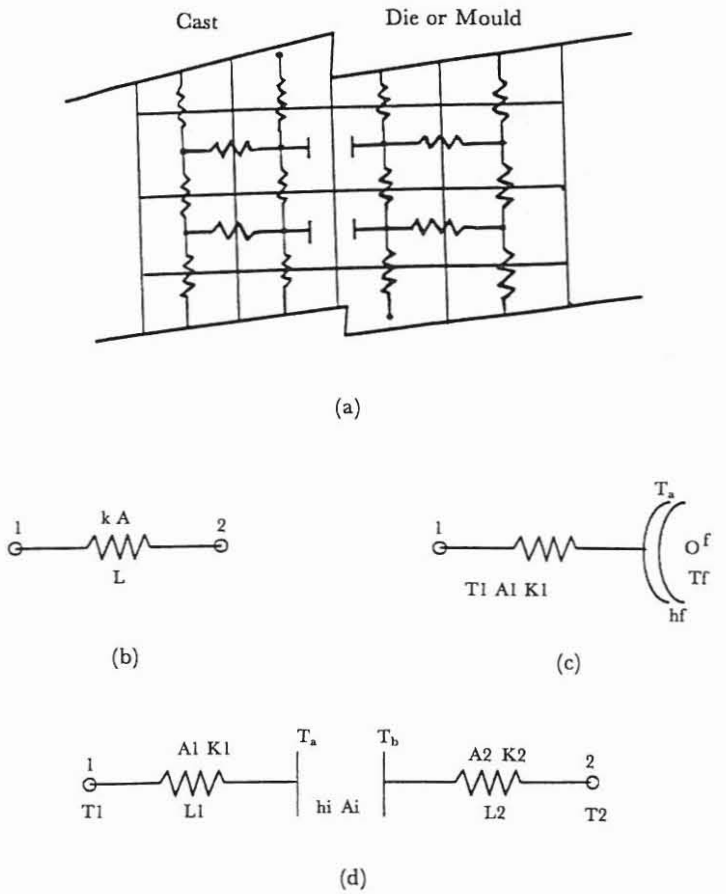

Fig. 1: Network link representation

$$q = -kA \, \frac{dT}{dx} \tag{1}$$

which may be converted into a matrix form as [4]

$$\frac{kA}{L}\begin{bmatrix} 1 & 1 \\ -1 & -1 \end{bmatrix}\begin{Bmatrix} T_1 \\ T_2 \end{Bmatrix} = \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix} \tag{2}$$

Where there are different materials joined at an interface (*Fig. 1c*), the matrix equation becomes

$$\frac{1}{\dfrac{L_1}{K_1\,A_1}+\dfrac{L_2}{K_2\,A_2}+\dfrac{1}{h_i\,A_i}}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} T_1 \\ T_2 \end{Bmatrix} = \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix} \tag{3}$$

and with heat loss to a cooling surface (*Fig. 1d*),

$$\frac{1}{\dfrac{L_1}{A_1 K_1} + \dfrac{1}{h_f A_f}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} T_1 \\ T_f \end{Bmatrix} = \begin{Bmatrix} Q_1 \\ Q_f \end{Bmatrix} \tag{4}$$

In a transient analysis energy is removed from the system by conduction, and this transient energy loss per unit volume can be expressed as

$$\dot{E} = \rho \; C \; \frac{dT}{dT}$$

or where phase change takes place over a finite temperature interval

$$\dot{E} = \rho \frac{dH}{dT} \frac{dT}{dt} \tag{5}$$

In discretised form, at timestep 'j' equation 5 can be expressed as

$$\dot{E} = \rho \frac{dH}{dT} \left[\frac{T_i^{J+1} - T_i^j}{\Delta t} \right]$$

This can be combined with the conduction matrices (equations 2, 3 or 4) to give an appropriate transient algorithm which may be explicit, implicit or explicit-implicit (Crank-Nicolson). For example, for an implicit formulation and a homogeneous conduction link

$$\rho V \frac{dH}{dT} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \frac{kA}{L} \Delta t \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} T_1^{j+1} \\ T_2^{j+1} \end{Bmatrix} = \rho V \frac{dH}{dT} \begin{Bmatrix} T_1^j \\ T_2^j \end{Bmatrix}$$

Similar equations may be derived by incorporating equations 3 and 4 for the appropriate heat removal path, where in the die or mould the enthalpy gradient (dH/dT) is replaced by the material specific heat. Thus for an implicit formulation, the general form of the matrix equation can be written as

$$[C] + \Delta t \, [K]]\{T^{j+1}\} = [C]\{T^j\}$$

Using this basis, the heat capacity matrix [C] needs to be recalculated at each time step to account for phase change and where nonlinear thermal conductivity {k(T)} is present, the equation set needs to be solved iteratively within each step with an update of the thermal conductivity at each iteration.

EXAMPLE CALCULATION

To test its use, the calculation procedure needs to be compared with either other mathematical models or experimental data, preferably both. As explained in Gethin *et al.* (1990), the continuum finite element thermal design tool has been compared with temperature measured on a die casting machine. Thus this forms a convenient set of results against which the present model may be tested.

A sectional view through the cast part and die is shown in Gethin *et al.* (1990). This has been selected since it represents a thick section through the casting metal injection system which will control the cooling transient duration in the cycle. The network discretisation for the part is shown in *Fig. 2*. Schematically, the discretisation features homogeneous links in the die and cast and convective links to ambient and cooling channels. Interface links are used at the cast-die interface to deal with the different materials on either side of the interface and to provide the facility to investigate the effect of pressure on the heat transfer across this gap (Nishida and Matsubora 1976). The model also features grid refinement at the various interfaces; this was found to be necessary to achieve adequate representation of the heat transfer, particularly at the cast to die interface where thermal gradients are steep.

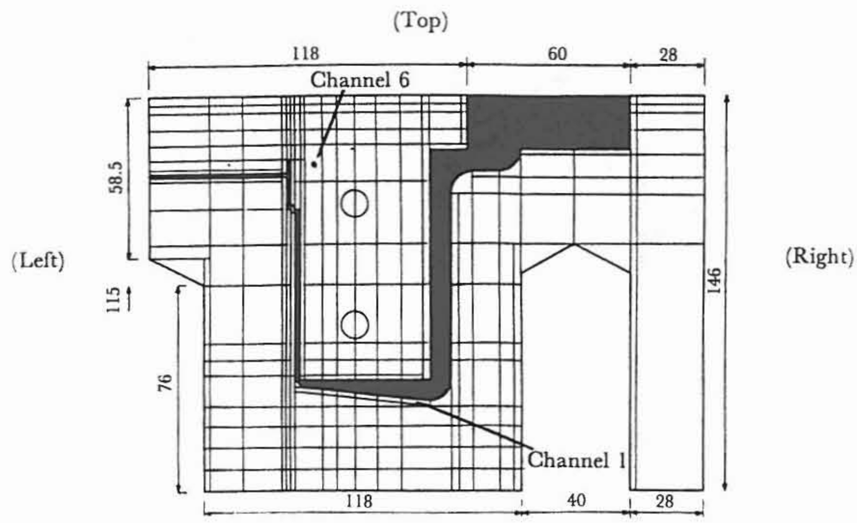

Fig. 2: The model mesh for a section

To complete the analysis requires boundary condition specification. The following, which reflect the die casting machine operation in the foundry, were used. For the cooling channels, a heat transfer coefficient of 9000 W/m°C was used with a water temperature of 24°C while the heat transfer coefficients are small at these surfaces. Finally at die mounting surfaces, the temperature was fixed at 150°C. For the temporal boundary condition, the cast metal was assumed to fill the die at its holding furnace temperature of 700°C. For the first cycle simulation, the die was at a uniform temperature of 150°C. During the course of calculation, a number of cycles were simulated with the end of cycle die temperature distribution used as a starting point for the next. This cyclic calculation was continued until the temperature fluctuations stabilized; this will be illustrated by means of an example.

RESULTS AND DISCUSSION

Fig. 3a illustrates a comparison between a thermal cycle measured in the die at thermocouple channel 1, excursions predicted suing a continuum finite element model (Gethin *et al.* 1990) and the network analysis. The network and finite element models follow the measured excursions closely when the die is closed, but deviate after it opens. This occurs since channel 1 is very close to the die surface and when the die opens the surface is exposed to ambient conditions with a consequent rapid fall in temperature. A typical response in the body of the die is shown in *Fig. 3b* for thermocouple channel

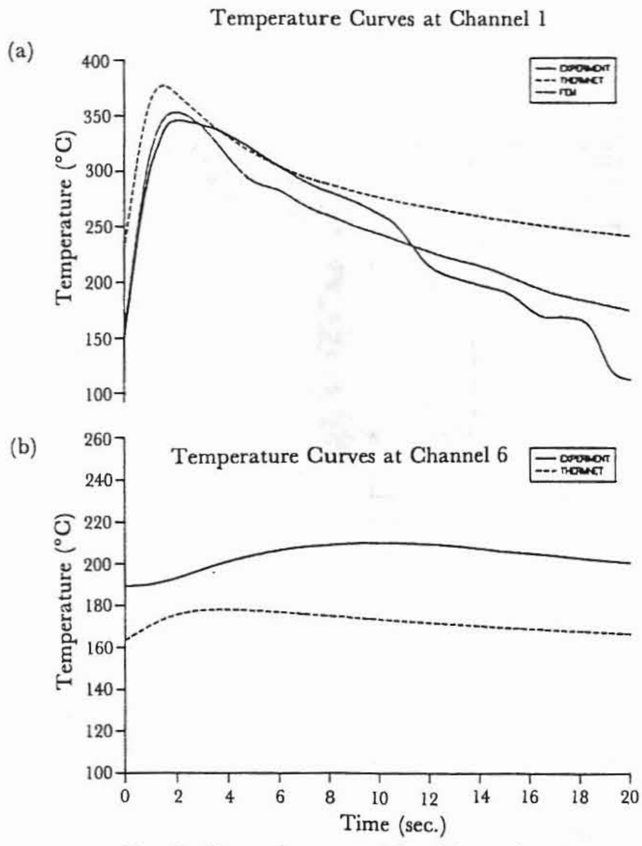

Fig. 3: Comparison of models with experiment

6. Clearly the measured and predicted excursions are not so extreme at this location and the agreement between the measured and predicted response is good. These comparisons suggest that the continuum finite element model gives marginally better results due to its ability to model part geometry more accurately. However, it requires a longer time to compute. Typically, the finite element analysis requires 120 min of CPU while the network calculation requires 10 min for a single cooling transient.

To obtain a more complete perception of the temperature response through the die and cast, shaded contour plots may be prepared as shown in *Fig. 4a*. This shows clearly the heat flow path and the area of hot molten metal in the thick feeding system. Further contours for the casting only are shown in *Fig. 4b-d* which suggest that complete solidification at a temperature of 600°C takes place by about 25 sec. This emphasizes the need for careful design of the cooling system, particularly in the die feeding section where the purpose of the cooling channel directly below the feeding system is to remove the heat rapidly and prevent premature die failure.

Thermal Stability

As explained previously, the thermal transient calculation was completed over a number of cycles until there was a stable thermal excursion established in the die. This technique circumvents the problem associated with prescribing the correct die temperature field at the start of the transient. Using this approach, the die is allowed to establish its own equilibrium temperature.

Fig. 5 illustrates the thermal response at selected points in both the cast part and the die over 6 cycles of different initial and uniform die temperatures and a casting cooling cycle time of 25 sec. Results are presented for node 290 (which corresponds to the location of thermocouple channel 1), node 291 which in the casting itself, but adjacent to channel 1, and node 370 which represents a coolant channel. Initial uniform temperatures considered were 50, 100, 150 and 200°C; from the results it can be seen that the thermal excursions have stabilized in an exponential manner after only 6 cycles. The stable temperature depends on the starting point value with the most significant increase occurring for 50°C starting temperature. This confirms the need for die heating to about 150-200°C before the commencement of casting to achieve a defect-free product.

Casting Cycle Time

Fig. 6 illustrates the cooling history at two points for different casting cycle frequencies. This shows that as the cycle time is reduced, so the stabile operating temperature become higher (Street 1986). This is a consequence of the larger amount of heat input into the die with the shorter casting cycle time, for the 10-sec cycle time, the stable temperature is about 350°C. This

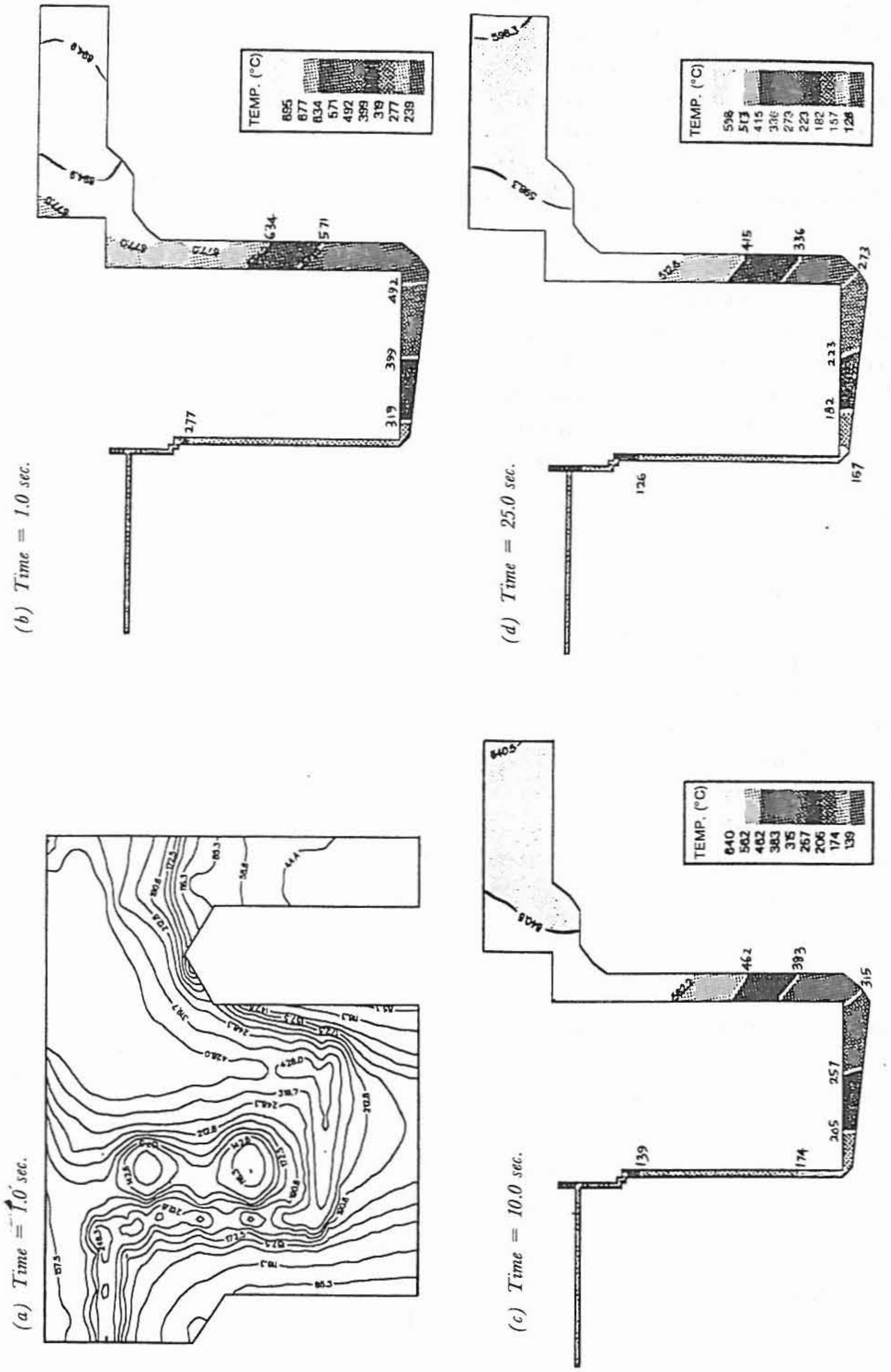

Fig. 4: Temperature contours in the die and casting

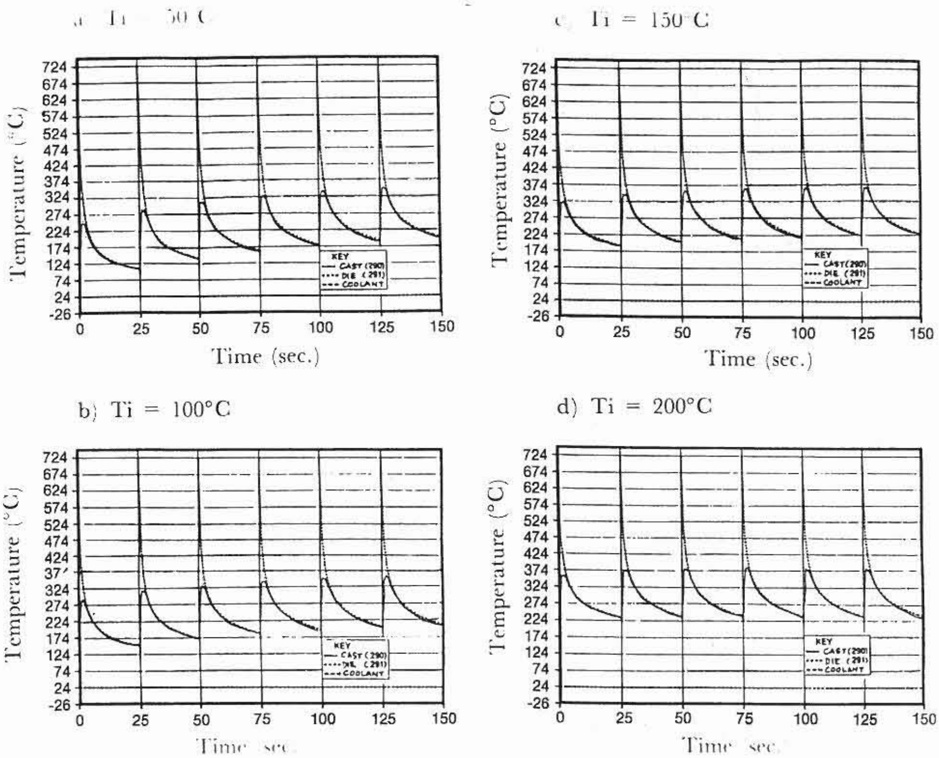

Fig. 5: Thermal stability for different initial die temperatures

may be compared with the stable temperature of about 250°C for the 25-sec cycle time.

Computational Time

In considering the computational aspects, the cyclic analysis presented in *Fig. 5* and *6* required about 55 min CPU time on a VAX 8820, whereas the continuum finite element analysis completed on an Apollo DN3000 workstation required about 120 min CPU time to complete a single cooling transient (Gethin *et al.* 1990). Thus the network approach is more economical and may be used to derive an initial design for the casting system.

CONCLUSION

It may be concluded from this study that the network analysis provides an economic route for the primary design of a die or mould. The requirements to model interface heat transfer effects and heat removal by cooling systems may be incorporated readily. The results from an analysis on a simple part compare well with experiment and with results from a continuum finite

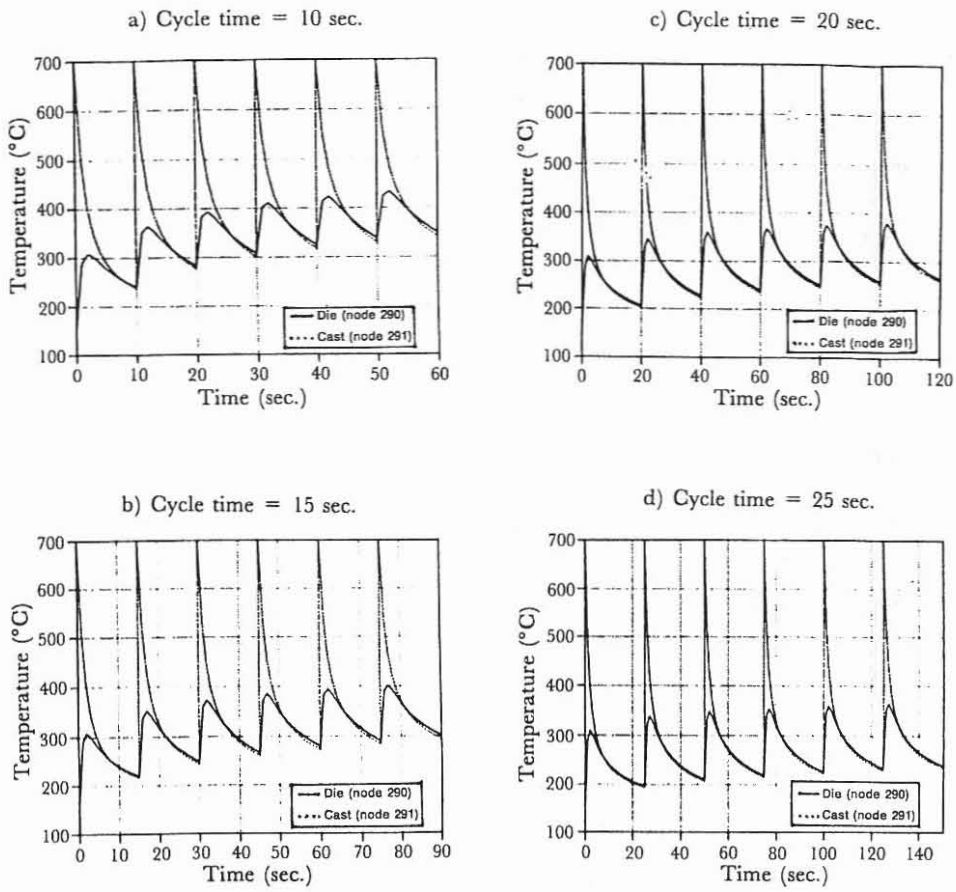

Fig. 6: The effect of temperature curves in the cast and die for different casting cycles

element model. The approach also allows the convenient modelling of a series of casting cycles to establish stable casting operating conditions.

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NOMENCLATURE

A	area
h_i	interface heat transfer coefficient
C	specific heat capacity
h_f	fluid heat transfer coefficient

H	enthalpy
k	thermal conductivity
L	length
t	time
T	temperature
ρ	density
V	volume

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