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Numerical modelling of heat transfer and solidification of continuously cast billets

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A simple model for evaluating the effect of changes in the heat transfer properties between mould and strand in a continuous caster is presented. The model is used to evaluate the heat transfer conditions for low alloy steels with two different carbon levels, and the results are compared to investigations of continuously cast billets. It is shown that the heat transfer conditions in the mould vary considerably between steels with different solidification mode (primary solidification as δ-ferrite or as austenite), which is dependent on their carbon content.

Key words: continuous casting, low alloy steels, numerical modelling.

Introduction

Previously the microstructure of the solid shell of continuously cast low alloy billets has been described in relation to the process parameters [1]. The investigations showed that the steels examined could be divided into two groups by their carbon content: steels containing 0.07–0.13 wt% C and steels containing approximately 0.46 wt% C. The steels of these two groups were shown to behave differently thermally and mechanically during casting.

In continuation of this work it was of interest to evaluate the heat transfer conditions between the mould and the strand in relation to the growth of the solid shell in the mould. It was decided to do this by the use of a simple one-dimensional numerical model representing a section through the centre of a face of the billet and the mould. The heat transfer properties between the strand and the mould were determined by calculating the shell thickness, and comparing the results with the shell thickness of continuously cast billets as described earlier [1].

Procedure

The mould is divided into three zones according to the heat transfer properties at the interface between the mould and its contents (i.e. the steel or the air above the meniscus): (see Fig. 1)

- **Zone I** is the top part of the mould which is above the meniscus, and where there is no contact between the mould and the strand.
- **Zone II** is the area around the meniscus where the solid shell is thin and weak [1–3], and there is good contact between the strand and the mould.
- **Zone III** comprises the largest part of the mould, where the thermal contraction of the strand causes the formation of an air-gap between the mould and the strand, thus in this area the heat transfer is low compared to that in zone II [1–3].

In zone I the heat transfer from the mould to the surroundings is very small compared to the heat transfer in zones II and III, and it is therefore considered to be equal to zero (adiabatic). The length of this zone is the same in all experiments. In the two other zones the heat transfer coefficients as well as the length of the zones can be varied in order to simulate different thermal conditions.

By changing the length and the heat transfer properties of zones II and III, the thickness of the solid shell and the temperatures in the mould and the strand are calculated and compared to the thickness of empty shells from breakouts that have previously been examined [1]. Through an iterative process:

- assessing the length of the zones and their respective thermal properties,
- calculating the shell thickness and comparing with measured results [1], and
- based on the calculations, selecting new values for the length of the zones and new heat transfer coefficients, then calculating, comparing, and so forth,

values for the heat transfer coefficients, and the position in the mould where the air-gap occurs, as well as the shell thickness in the mould, are found.

The present work was carried out at The Department of Metallurgy at The Technical University of Denmark by Niels Tiedje as a part of his masters thesis.

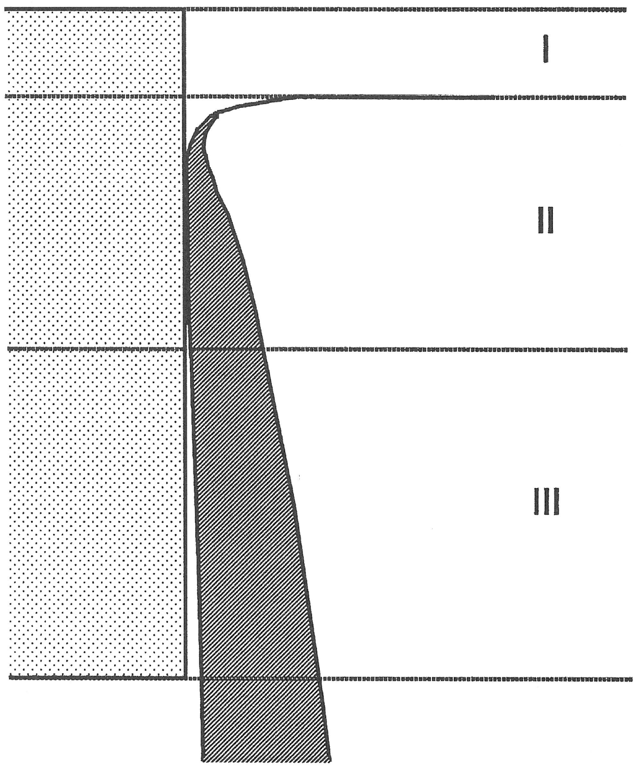
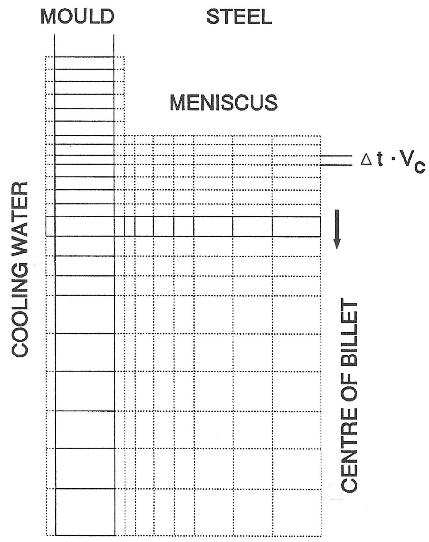


Fig. 1. *Zones in the continuous casting mould in which different heat transfer properties from the mould to the surroundings are found.*



Element	1 - 2	3 - 4	5 - 7	8 - 9	10 - 29	30	31
Size, Δx [mm]	12	10	5	2.5	1	12	1

Number of time-steps	1 - 10	11 - 22	23 - 37	38 - 60
Δt [s]	0.30	0.20	0.50	1.10

Fig. 2. *Schematic diagram of the elements used in the numerical model. The table shows the size and the number of the elements, starting at the centre of the strand.*

The calculations were carried out for steels in the two groups mentioned above, i.e.

- Group I: steels with carbon contents ranging form 0.07 to 0.13 wt%.
- Group II: steels containing about 0.46 wt % C.

The numerical model

The model covers only the mould and the strand, and is based on a simple one-dimensional implicit routine, see appendix.

A series of elements covering the centre of the billet, the mould, and the cooling water on the outside of the mould is followed from the top of the mould to the bottom.

For each element three equations with three unknown temperatures have to be solved; this is done by a simple iterative process (see appendix). Thermal data for the calculations are collected from Sahm & Hansen [4].

To solve the set of equations the following boundary conditions are used:

- the temperature of the cooling water is kept constant at 20°C (according to Lodin [5] the temperature of the cooling water at the Danish Steel Works, where the previously examined billets were cast, changes approximately 6°C during casting having a mean temperature of about 20°C).
- for reasons of symmetry there is no heat transfer across the centre of the mould, thus the temperature of two elements on either side of the centre will be the same.

The row of elements are followed from the top of the mould to the bottom, assuming a casting speed (v_c) of 2 m/min, and using the time steps according to Figure 2. Thus for each calculation of the temperatures in the row of elements the row moves the distance $\Delta t \cdot v_c$ down the mould.

In order to simulate steady state conditions in the mould this process is repeated a number of times, using the calculat-

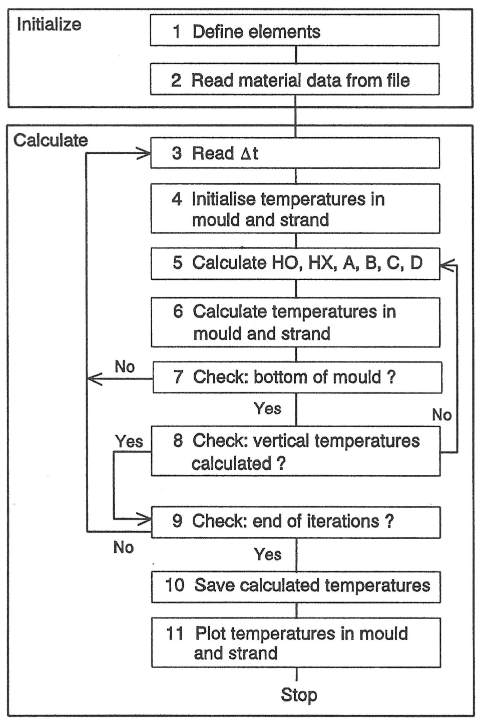


Fig. 3. *Flow chart for the numerical model.*

ed mould temperatures as new initial temperatures, until the temperatures in the mould do not change significantly over a number of iterations.

The above described model does not account for the vertical heat transfer in the mould and the steel, and experiments showed that due to the large thermal conductivity of copper, the calculated mould temperatures were incorrect, particularly at the bottom of the mould. Therefore the model was modified in a simple way to account for the vertical heat transfer in the mould. Following each iteration the change in temperatures in the vertical direction of the mould was calculated using a one-dimensional routine similar to the one used on the row of elements covering the mould and strand.

Figures 2 and 3 show, schematically, the network used for the calculations, and a flow chart for the model.

Results and Discussion

The purpose of this work has been to investigate heat transfer properties of the cooling water, the mould, the strand, and their respective interfaces in relation to the solidification process. Therefore the following experiments were carried out:

- the heat transfer coefficients between the mould and strand, and the position in which the formation of the air-gap between the strand and the mould occur has been fitted to match the previously measured thickness of shells of continuously cast billets [1],

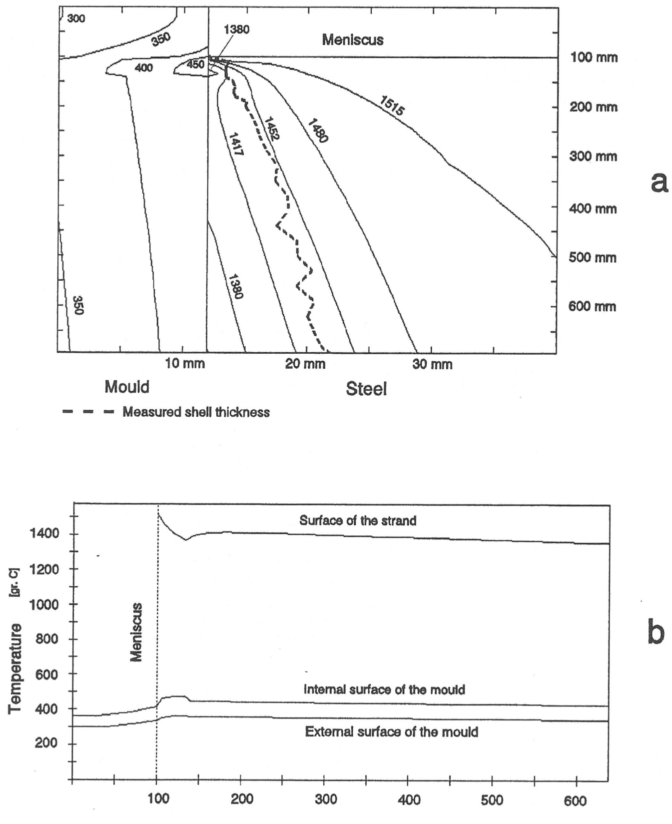


Fig. 4. *a) Distribution of temperatures in the mould and strand for a steel containing 0.13 wt% C, b) surface temperatures of the mould and the strand. Heat transfer coefficients are 2000 and 400 W/ $m^2 \cdot K$ in zones II and III respectively, the air-gap is formed 33 mm below the meniscus.*

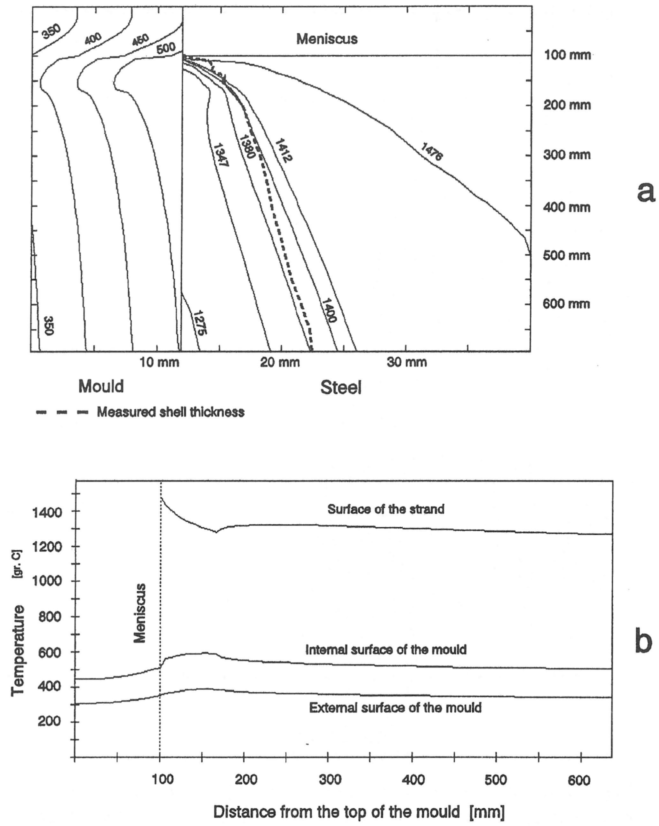


Fig. 5. *a) Distribution of temperatures in the mould and strand for a steel containing 0.46 wt% C, b) surface temperatures of the mould and the strand. Heat transfer coefficients are 2200 and 600 W/ $m^2 \cdot K$ in zones II and III respectively, the air-gap is formed 66 mm below the meniscus.*

- the effect of a large change in the heat transfer coefficient between the cooling water and the mould has been tested.

Figures 4 and 5 show the result of calculations carried out for steels in group I and II respectively. The figures show isotherms in a section through the mould and the outer 28 mm of the strand in the full length of the mould, as well as the shell thickness of a strand of similar composition, as reported in [1]. The measured shell thickness is obtained by measuring the thickness of the solid shell left in the mould after a breakout has occurred. This shell thickness represents the thickness of the completely solid shell plus a certain amount of the mushy zone. When a breakout occurs, a part of the mushy zone is washed out with the liquid metal that flows out from the damaged shell. That part of the mushy zone which is left attached to the solid shell is based on earlier investigations [1,10], estimated as corresponding to a fraction solid in the range of 0.75 to 1.00. Thus, in Figures 4 and 5, the broken line representing the measured shell thickness is positioned between $f_s = 1.0$ and $f_s = 0.75$.

Four of the isotherms represent different levels of fraction solid according to Table 1. The liquidus temperature is calculated according to [6], and the temperatures for $f_s = 0.9$, 0.75 and 0.0 are calculated as described by Kurz & Fisher [7], using a modified version of Scheil's equation, accounting for complete mixing in the liquid and diffusion of solute (in this case carbon) in the solid state.

The steels need to be cooled to a temperature somewhat below below the solidus temperature before their ductility begins to increase [6–10]. The temperatures for the onset

Table 1. *Temperatures corresponding to f_s equal to 0.0, 0.75, 0.9, and 1.0, and the temperature for the onset of ductility.*

Carbon content	Temperature [°C]				
	$f_s = 0.0$	$f_s = 0.75$	$f_s = 0.9$	$f_s = 1.0$	Onset of ductility
0.13	1515	1480	1452	1417	1380
0.46	1476	1412	1380	1347	1275

of ductility are also shown in Table 1, and plotted in Figures 4 and 5.

Both Figures 4 and 5 show that, just below the meniscus, the temperatures in the mould are very high, approaching 500°C, and the shell grows rapidly in thickness. As the air-gap is formed, the temperatures on the inner surface of the mould quite rapidly decrease by about 50°C, whereafter the temperature rises slightly towards the bottom of the mould.

Prior to the formation of the air-gap heat transfer coefficients in the range of 1700–2500 $W/m^2 \cdot K$ were used for steels in both group I and II (see Table 2) resulting in rapid shell growth, corresponding to the measured shell thickness immediately below the meniscus. These values correspond well with the heat transfer coefficent of 2800 $W/m^2 \cdot K$ found by Michalek *et al.* [11].

Lower values (1000–1400 $W/m^2 \cdot K$) did not cool the strand sufficiently to ensure the formation of a solid shell during the first approximately 100 mm below the meniscus. The high carbon steels are particularly sensitive to variations in the heat transfer coefficient at the meniscus due to their relatively large solidification range (T_l–T_s = 129°C).

For the steels having a low carbon content, the air-gap is formed 17 to 50 mm below the meniscus, while for the high carbon content steels the air-gap is formed at a somewhat later stage, 67–100 mm below the meniscus, depending on the size of the heat transfer coefficient.

The difference in the length of zone II between the two groups of steels is a result of the difference in the size of their solidification ranges and their different thermal contraction. To form a solid shell in the high carbon steels more heat will have to be removed from the steel than is the case for the low carbon steels. As the heat transfer coefficients are the same for both types of steels, it will take longer to produce a solid shell which is strong enough to withstand the ferrostatic pressure for the high carbon steels than for the steels with a low carbon content. Once the shell is sufficiently strong the thermal contraction of the low carbon steels is larger than for the high carbon steels, as the phase transformation following solidification causes an extra reduction in volume.

Table 2. *Heat transfer coefficients used for the calculations, as well as the distance below the meniscus at which the air-gap is formed, for steels of different carbon content.*

Carbon content [mm]	Heat transfer coefficients [$W/m^2 \cdot K$]		Distance to the formation of air-gap [mm]
	Zone II	Zone III	
0.07 wt%	1700–2500	200–400	17–50
0.13 wt%	1700–2500	200–400	17–50
0.46 wt%	1700–2500	400–600	67–100

Once the air-gap is formed, the heat transfer between the strand and the mould is reduced drastically. For the low carbon steels, values in the range of 200 to 400 $W/m^2 \cdot K$ were found. For the steels in group II the values found were somewhat larger (400–600 $W/m^2 \cdot K$), indicating that these steels are cooled more efficiently. Michalek *et al.* [11] found heat transfer coefficients of about 1000 $W/m^2 \cdot K$, which is larger than the present findings, this may be due to variations in mould design and lubricant.

In a previous article [1] it was shown that the outer surfaces of billets of the two groups of steels are very different, the low carbon steels having a very rough surface, while the high carbon steels have a smooth surface. The rough surface reduces the overall contact to the mould, and is thus responsible for a reduced cooling of the strand.

Using the lowest values (200 $W/m^2 \cdot K$) for the heat transfer coefficients in zone III for the low carbon steels causes the shell to remelt on the inside due the heat stored in the molten core. This corresponds very well with previous findings [1], where signs of remelting of the shell was found.

The high carbon steels, for which larger heat transfer coefficients in zone III were used, showed no sign of remelting, and, in spite of their considerably larger solidification range, they grew a thicker solid shell.

The temperatures in the mould are quite high. In the low carbon steels temperatures on the face close to the mould are in the range 400–500°C, and in the high carbon steels, where good contact to the mould is maintained for a longer period of time, temperatures at the meniscus approach 600°C. This is partly explained by the somewhat "simple" model which accounts neither for horizontal heat flow parallel to the surface of the mould nor for the extra cooling at the corners of the mould. The temperatures in the strand are quite large and in most cases above the temperature for the onset of ductility, which may be a result of the large mould temperature and the simplicity of the model. Therefore the primary results obtained by this model are those concerning the relationship between the heat transfer properties between the mould and strand, and the growth of the solid shell during the casting process.

In order to test the influence of a change in the cooling of the mould, the heat transfer coefficient between the mould and the strand was doubled, from 15 000 $W/m^2 \cdot K$ to 30 000 $W/m^2 \cdot K$. The primary effect of this was that the temperatures on the face of the mould adjacent to the cooling water were lowered by approximately 50°C, whereas the temperatures in the strand were unchanged. Comparing the resistance to heat transfer (the reciprocal of the heat transfer coefficient) at the two surfaces of the mould, it is evident that halving the resistance at the interface between the mould and the water from $6.7 \cdot 10^{-5}$ $m^2 \cdot K/W$ to $3.3 \cdot 10^{-5}$ $m^2 \cdot K/W$ may result in changes in the mould temperatures, but compared to the resistance at the air-gap of approximately $2.5 \cdot 10^{-3}$ $m^2 \cdot K/W$ such a change is not capable of changing the temperatures in the strand. Consequently, if it is desired to change the cooling of the strand, this should be done by changing the heat transfer coefficients between the strand and the mould, particularly in zone III. This may be done by using a different mould lubricant, or by adjusting the taper of the mould to specifically suit the steel to be cast.

Particularly for the low carbon steels, this and previous examinations [1] point towards increasing the heat transfer coefficient in zone III. Such a change may be provided by using mould powders as lubricant instead of rapeseed oil;

as powders generally act to ensure a more even cooling of the strand (by lowering the heat transfer in zone II and increasing the heat transfer in zone III) than does oil [12,13].

Conclusion

A simple numeric model for evaluating the effect of changes in the heat transfer conditions in the mould of a continuous caster is presented. It is shown that low alloy steels can be divided into two groups depending on their carbon content: "low carbon steels" containing 0.07 to 0.13 wt% carbon, and "high carbon steels" containing approximately 0.46 wt% carbon. Steels in the two groups are cooled differently in the mould, leading to different growth rates for the solid shell.

At the meniscus, before the formation of the air-gap, the steels are subjected to the same cooling conditions, and heat transfer coefficients in the range 1700–2500 $W/m^2 \cdot K$ has been found, resulting in rapid growth of the shell.

Due to their relatively small solidification range and large thermal contraction, the low alloy steels rapidly form a thick solid shell; resulting in the formation of the air-gap close to the meniscus (17–50 mm below the meniscus). The high carbon steels have a larger solidification range and less thermal contraction, thus they remain in good contact with the mould for a longer period (67–100 mm below the mould).

After the formation of the air gap, low carbon steels are cooled less than high carbon steels (200–400 $W/m^2 \cdot K$ and 400–600 $W/m^2 \cdot K$ respectively) due to differences in surface morphology and thermal contraction.

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Appendix A

The temperatures in the strand and the mould are described by the one-dimensional Fourier equation for conductive heat transfer: [14,15]

$$\frac{\varrho \cdot c_p}{\lambda}\left(\frac{\partial T}{\partial t}\right) = \left(\frac{\partial^2 T}{\partial x^2}\right) \tag{A1}$$

Using a finite difference approximation, the above equation becomes [14,15]:

$$(\varrho \cdot c_p)_i \cdot \frac{\Delta T}{\Delta t} = \frac{(T_{i-1,New} - T_{i,New})}{\Delta x_i \cdot \left(\frac{\Delta x_i}{2 \cdot \lambda_i} + \frac{\Delta x_{i-1}}{2 \cdot \lambda_{i-1}} + R_{i-1,i}\right)} + \frac{(T_{i+1,New} - T_{i,New})}{\Delta x_i \cdot \left(\frac{\Delta x_i}{2 \cdot \lambda_i} + \frac{\Delta x_{i+1}}{2 \cdot \lambda_{i+1}} + R_{i,i+1}\right)} \tag{A2}$$

where indices "Old" and "New" refer to temperatures before and after the passing of the time Δt, and $R_{i-1,i}$ and $R_{i,i+1}$ are the thermal resistances between elements $i-1$ and i, and elements i and $i+1$ respectively defined by:

$$R = \frac{\Delta x}{2 \cdot A \cdot \lambda}$$

thus the temperature in element i is described by:

$$HO_i \cdot T_{i,Old} = -HX_i \cdot T_{i-1,New} + (HO_i + HX_i + HX_{i+1}) \cdot T_{i,New} - HX_{i+1} \cdot T_{i+1,New} \tag{A3}$$

Where:

$$HO_i = \Delta x_i \cdot (\varrho \cdot c_p)_i / \Delta t$$

and

$$HX_i = (\Delta x_i / 2 \cdot \lambda_i + \Delta x_{i-1} / 2 \cdot \lambda_{i-1} + R_{i-1,i})^{-1}$$

For each element a set of three equations similar to eqn. A3 have to be solved for each time step, Δt.

In the case of:

$A_i = -HX_i$,
$B_i = HO_i + HX_i + HX_{i+1}$,
$C_i = -HX_{i+1}$, and
$D_i = HO_i \cdot T_{i,Old}$

eqn. A3 becomes:

$$D_i \cdot T_{i,Old} = A_i \cdot T_{i-1,New} + B_i \cdot T_{i,New} + C_i \cdot T_{i+1,New} \tag{A4}$$

For the N number of elements, using the boundary conditions:

$A_1 = 0, B_1 = 1, D_1 = 20°C$, and
$A_N = -1, B_N = 1, D_N = 0$

the N equations may be written as follows:

$$\begin{bmatrix} B_1 C_1 \ 0 & \cdot & \cdot & \cdot & 0 \\ A_2 B_2 C_2 \ 0 & \cdot & \cdot & \cdot & 0 \\ 0 \ A_3 B_3 C_3 0 & \cdot & & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & \cdot & \cdot & \cdot & 0 A_{N-1} B_{N-1} C_{n-1} \\ 0 & \cdot & \cdot & \cdot & 0 \quad A_N \quad B_N \end{bmatrix} \cdot \begin{bmatrix} T_{1,New} \\ T_{2,New} \\ T_{3,New} \\ \cdot \\ \cdot \\ T_{N-1,New} \\ T_{N,New} \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ \cdot \\ \cdot \\ D_{N-1} \\ D_N \end{bmatrix} \tag{A5}$$

This set of equations are solved by a simple iterative procedure: [16]

$$T_{i,New} = G_i - \frac{C_i \cdot T_{i+1,New}}{F_i} \tag{A6}$$

where

$$F_1 = B_1$$

$$F_i = B_i - \frac{A_i \cdot C_{i-1}}{F_{i-1}} \quad , \quad i = 2,3,4,.....,N$$

$$G_i = \frac{D_i - A_i \cdot G_{i-1}}{F_i} \quad , \quad i = 2,3,4,.....,N$$

thus by iterating backwards from N to 2, the new temperatures are found.