論 文

# L형주철금형에 주입한 순수한 알미늄의 IAD법에 의한 응고해석

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# Numerical Analysis of the Solidification of L-Shaped Pure Aluminum Castings in Cast Iron Molds with IAD Method

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초 록

IAD( Implicit Alternative Direction ) FDM을 사용하여 금형에서의 L형 순수알미늄 주물에 대하여 그 응고상황의 수치적 해석을 2차원적으로 시도하였다. 계산은 주형비 ( 주형의 부피／주물의 부피 ) 에 따라 금형표면에서의 대류현상과 금형／주물계면에서의 Air-gap 형성 현상을 고려에 넣은 경우와 그렇지 않은 경우로 나누어 각각 콤퓨터에 의해 계산하여 그 결과를 비교하였다. 또한 금형／주물 계면주위의 온도구배를 구함으로써 Air-gap이 열전달에 미치는 영향을 검토하였다.

이와같은 시도에 의하여 주물의 응고시간, 응고방향 Hot spot의 위치 등 주조에 있어서 매우 중요한 사항들을 알아내는데 Numerical Analysis 이 매우 유용한 방법임을, 특히 금형표면에서의 대류현상과 금형／주물 계면에서의 Air-gap 형성현상을 고려에 넣은 경우에 더욱 정확한 결과를 기대할 수 있다는 것이 확인되었다.


## I. INTRODUCTION

The information such as the effect of mold ratio on the casting solidification time, the solidification direction, and the location of hot spots, etc., are meaningful in the foundry. Recently, many researches to obtained the information mentioned above (and many other useful information) have been successfully underway by applying the numerical method in analysizing the solidification process of castings on the basis of the heat transfer theory.(1), (11)

The problem of analyzing the solidification process of molten metal is cut down to that of obtaining the solution of the differential equations derived from Fourier's law of conduction. The FDM (Finite Difference Method) and FEM (Finite Element Method) are the general methods in this field, and have turned out to be very accurate through comparing the results of them to those of several experiments.(1), (9), (10)

However, it has also been pointed out that the

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accuracy of the numerical methods is within certain limits because some factors such as; the temperature change at the mold surface, the air-gap formation phenomenon at the mold/casting interface, and the change in thermal properties of materials involved, are ignored.[1], [2], [3]

In this research, taking those factors mentioned above into consideration, the simulation of the L-shaped section of pure-Al casting in cast iron molds has been attempted 2-dimensionally. The L-shape is one of the basic shapes in the foundry. The simulation has been carried out with the IAD (Implicit – Alternating Direction, FDM) method.

The calculation has been performed in Fortran 77 both with and without taking the two factors (the convection phenomenon at the mold surface and the air-gap formation at the interface) into consideration.

## II. ASSUMPTIONS, SIMULATION, AND CALCULATION

### II–1. ASSUMPTIONS AND INITIAL CONDITIONS

(1) Assumptions

i) The mold is instantaneously filled with liquid metal at the pouring temperature.
ii) Once the mold is filled, the liquid metal is stagnant, i.e., no convective mass & energy transport in the liquid phase is considered.
iii) Air-gap of finite thickness forms instantaneously after an elapse of some seconds from the instant the mold is filled.
iv) Natural convective heat transfer occurs from the outside surface of the mold to atmosphere.
v) Before air-gap formation, heat transfer between casting and mold is essentially by condition.
vi) After air-gap formation, heat transfer between casting and mold is by conduction and radiation through the gap layer.
vii) The mold interface temperature is treated as the ambient temperature for casting and vice versa.[1], [10]

(2) Initial Conditions

i) The mold is at a uniform preheat temperature of 250°C.
ii) The molten metal is at a uniform temperature, viz., pouring temperature, 750°C.
iii) Neglecting any thermal contact resistence, the initial mold/casting interfacial temperature ($T_{m/co}$) is like the following, where $T_{mo}$ and $T_{co}$ are the initial temperature of mold and casting respectively.[18]

$$T_{mo/co} = T_{mo} + \frac{T_{co} - T_{mo}}{1 + \frac{K_m}{K_c}\sqrt{\frac{\alpha_c}{\alpha_m}}} \qquad (1)$$

Here,

$K_m$ ; thermal conductivity of mold
$K_c$ ; thermal conductivity of casting
$\alpha_m$ ; thermal diffusivity of mold
$\alpha_c$ ; thermal diffusivity of casting

### II–2. SIMULATION

(1) Basic Concept

Heat conduction can be described by Fourier's law in the following way:

$$Q_x = -KA\frac{dT}{dx} \qquad (2)$$

Here,

$Q_x$ ; heat transfer rate (x direction) Cal/sec
A ; area normal to x direction $cm^2$
$\frac{dT}{dx}$ ; temperature gradient in x direction °C/cm
K ; thermal conductivity Cal/cm °C sec

Heat flow by convection at a surface or an interface can also be described by Newton as follows:

$$Q = hA(T_s - T_f) \qquad (3)$$

Here,

Q ; heat flow

$T_s$ ; temperature of solid °C

$T_f$ ; temperature of fluid °C

h ; surface heat transfer coefficient Cal/cm °C sec.

With the two equations (2), (3) above, heat balance is achieved for every nodal point.

(2) 2-Dimensional Model of Solidification

If the casting is long enough so that the end and riser-hear transfer effects can be neglected, i.e., if the Z-dimension is infinite, the problem can be considered 2-dimensional as shown in figure 1.

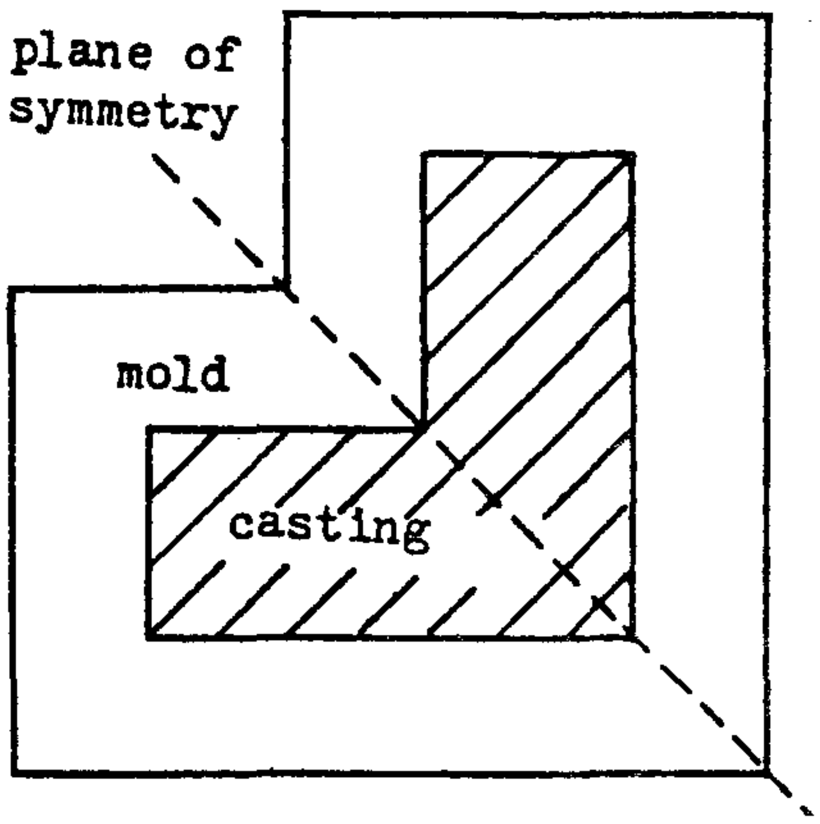


Figure 1. Planar Section of L-shaped casting showing symmetry

Because of the symmetry about the 45° diagonal, it suffices to consider only on leg of the "L". This is shown in figure 2. Then the casting and the mold

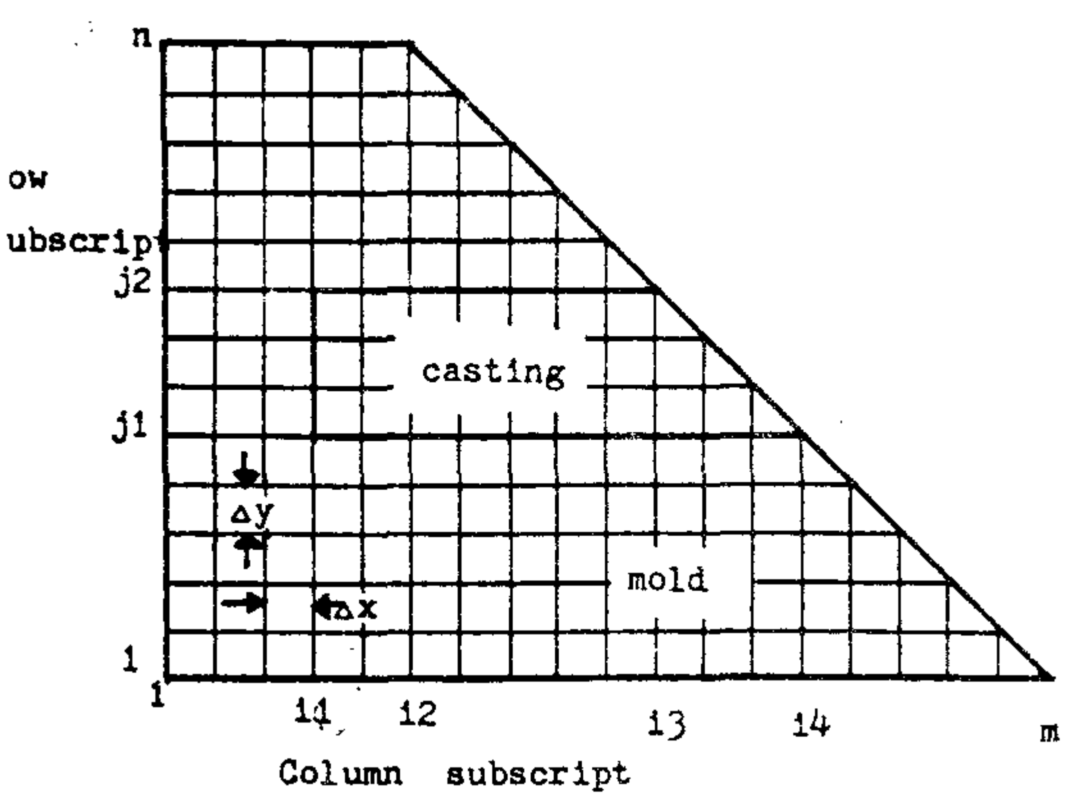


Figure 2. Illustrative Representation of grid points of mold & casting

are divided into elements with the dimension of $\Delta x$ and $\Delta y$ in x and y direction respectively.

Here, the $\Delta x$ and $\Delta y$ are taken to be equal for convenience sake. The total number of nodal points in x and y direction are represented by m and n respectively and other particularly important points in calculation are represented by i1, i2, j1, j2, ... , etc., in order to be easily replaced when calculating various cases.

(3) Boundary conditions & Thermal Properties of Materials Involved

i) The ambient temperature, $T_A$, is taken to be 25°C.

ii) The 45° diagonal behaves as an insulating surface across which there is zero flux. Thus, from Fourier's law,

$$\frac{dT}{dn} = 0 \quad \text{along the } 45^\circ \text{ diagonal}$$

iii) There is also continuity of flux across the mold/casting interface, that is;

$$K_c \frac{dT_c}{dn} = K_m \frac{dT_m}{dn}$$

iv) Thermal properties of materials (heat conductivity, specific heat, density, etc.) are treated as functions of temperature. Especially, the latent heat of aluminum is dealt with by establishing an imaginary interval on its specific heat curve according to the equation below;[18]

$$\Delta H_{fusion} = \int_{T_s}^{T_1} (C_p^* - C_p)\, dT$$

(4) Simulation for Every Grid Point

The IAD method is chosen in this research because it is free from the stability & the convergency conditions from which the explicit FDM suffers, and because it can avoid a lot of calculation which the implicit FDM requires, without losing accuracy.

The basic principle of the IAD method is as follows; Each time step, $\Delta t$, is divided into two half-time steps. In the first half-time step, $\Delta t/2$, the implicit method is applied for the x-direction and the explicit method for the y-direction. In the last half time step, $\Delta t/2$, the opposite method is applied for both directions.

For example, if the IAD method is applied for a general point (not on the surface or interface) between the time-step $t_n$ and $t_{n+1}$' the equations can be described in this way;[19]

$$\frac{T^*_{i-1,j} - 2T_{i,j} + T^*_{i+1,j}}{(\triangle x)^2} + \frac{T_{i,j-1,n} - 2T_{i,j,n} + T_{i,j+1,n}}{(\triangle x)^2} = \frac{1}{\alpha_{ijn}} \frac{T_{ij} - T_{ijn}}{\triangle t/2}$$

$$\frac{T_{i-1,j} - 2T_{ij} + T_{i+1,j}}{(\triangle x)^2} + \frac{T_{i,j-1,n+1} - 2T_{i,j,n+1} + T_{i,j+1,n+1}}{(\triangle x)^2} = \frac{1}{\alpha_{ijn}} \frac{T^*_{i,j,n+1} - T^*_{i,j}}{\triangle t/2}$$

Here,

$T_{i,j,n}$ ; the temperature of (i,j) node at time step n

$T^*_{i,j}$ ; the intermediate temperature just after the first half time step $\Delta t/2$

The equations (4), (5) are rearranged in the form of (4)' (5)' below.

$$-T^*_{i-1,j} + 2(Z_{i,j,n}+1)T^*_{i,j} - T^*_{i+1,j} = T_{i,j-1,n} + 2(Z_{i,j,n}-1)T_{i,j,n} + T_{i,j+1,n}$$

$$-T_{i,j-1,n+1} + 2(Z_{i,j,n}+1)T_{i,j,n+1} - T_{i,j+1,n+1} = T^*_{i-1,j} + 2(Z_{i,j,n}-1)T^*_{i,j} + T^*_{i+1,j}$$

Here,

$$Z_{i,j,n} = \frac{(\triangle x)^2}{\alpha_{i,j,n}\triangle t}$$

A tridiagonal simultaneous equation is obtained if the process shown above is applied to every grid point. For the sake of convenience, all equations are represent in this form: $A_iT_{i-1} + B_iT_i + C_iT_{i+1} = D_i$ (For example, in equation (4)', $A_i = C_i = -1$, $B_i = 2(Z_{i,j,n} + 1)$, $D_i = T_{i,j-1,n} + 2(Z_{i,j,n} - 1)T_{i,j,n} + T_{i,j+1,n}$). In this way, the tridiagonal matrix coefficients of all grid points are represented below:

(i) Internal points

First half : $A_i = C_i = -1$,
$B_i = 2(Z+1)$,
$D_i = T_{i,j-1,n} + 2(z-1)T_{i,j,n} + T_{i,j+1,n}$

Second half : $A_j = C_j = -1$,
$B_j = 2(z+1)$,
$D_j = T^*_{i-1,j} + 2(z-1)T^*_{i,j} + T^*_{i+1,j}$

Here,

$$Z = (\triangle x)^2/(\alpha_{i,j,n}\triangle t)$$

(ii) Points 45° Line of Symmetry

First half : $A_l = -1$,
$B_l = (z+1)$,
$D_l = T_{1,j-1,n} + (z-1)T_{1,j,n}$

Second half : $A_j = -1$,
$B_j = (z+1)$
$D_j = T^*_{1-1,j} + (z-1)T^*_{1,j}$

Here,

$$Z = (\triangle x)^2/(\alpha_{1,j,n}\triangle t)$$

(iii) Points on the Surface of the Mold

(a) $I = 1$, $J = 1$

First half : $B_i = 1+z$,
$C_i = -1$,
$D_i = 2BIT_A + (z - 2BI - 1)T_{1,1,n} + T_{1,2,n}$

Second half : $B_j = (1+z)$
$C_j = -1$,
$D_j = 2BIT_A + (z - 2BI - 1)T^*_{1,1} + T^*_{2,1}$

Here,

$BI = h\triangle x/k$,
$Z = (\triangle x)^2/(\alpha_{i,j,n}\triangle t)$

* The definitions of Z and BI below from now are the same as above.

(b) $I = 1$, $J = N$

First half : $B_i = 1+z$,
$C_i = -1$,
$D_i = 2BIT_A + (z - 1 - 2BI)T^*_{1,N,n} + T^*_{1,N-1,n}$

Second half : $A_j = -1$,
$B_j = 1+z$,

$D_j = 2BIT_A + (z - 2BI + 1)$
$T^*_{1,N} + T^*_{2,N}$

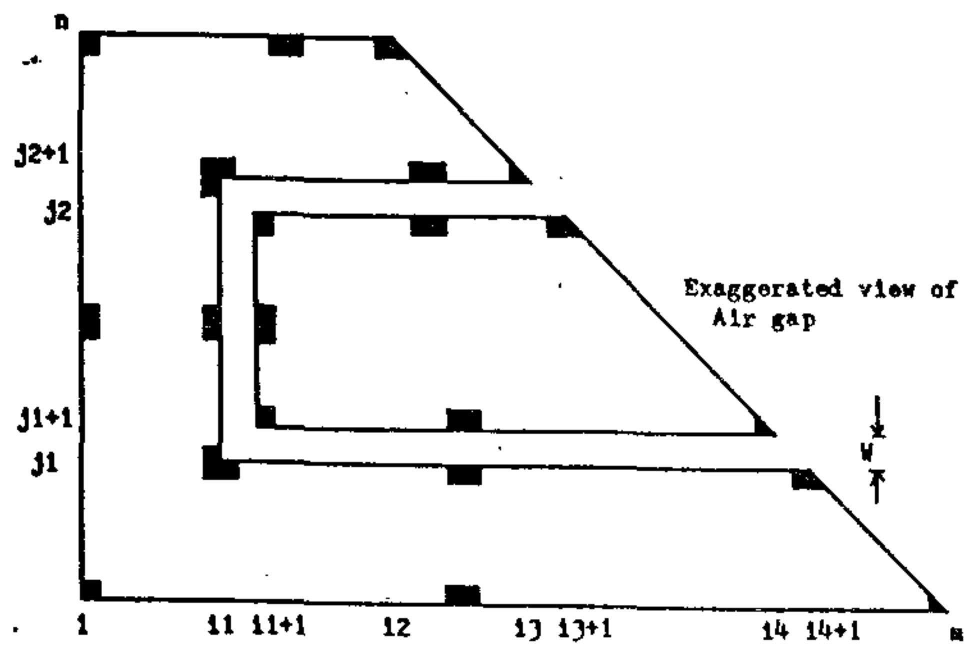


Figure 3. Illustrative Representation of Particularly important Grid Points

(c) $I = I2$, $J = N$

First half : $A_i = -1$,
$B_i = 1 + 1.5z$,
$D_i = BIT_A + (1.5z - BI - 2)$
$T_{i2,N,n} + 2T_{i2,N-1,n}$

Second half : $A_j = -2$,
$B_j = 2 + 1.5z$,
$D_j = BIT_A + (1.5z - BI - 1)$
$T^*_{i2,N} + T^*_{i2-1,N}$

(d) $I = M$, $J = 1$

First half : $A_i = -1$,
$B_i = (1 + 0.5z)$,
$D_i = BIT_A + (0.5z - BI)$
$T_{M,1,n}$

Second half : $B_j = BI + 0.5z$
$D_j = BIT_A + T^*_{M-1,1} + (0.5z - 1)\,T_{M,1}$

(e) $I = 2 \sim M-1$, $J = 1$

First half : $A_i = C_i = -1$,
$B_i = 2(1+z)$,
$D_i = 2BIT_A + 2(z - BI - 1)$
$T_{i,1,n} + 2T_{i,2,n}$

Second half : $B_j = 2(1+z)$,
$C_j = -2$,
$D_j = T^*_{i-1,1} + 2(z - BI - 1)T^*_{i,1}$
$+ T^*_{i+1,1} + 2BIT_A$

(f) $I = 1$, $J = 2 \sim N-1$

First half : $B_i = 2(1+z)$,
$C_i = -2$,
$D_i = 2BIT_A + 2(z - BI - 1)$
$T_{i,j,n} + T_{i,j-1,n} + T_{i,j+1,n}$

Second half : $A_j = C_j = -1$,
$B_j = 2(1+z)$,
$D_j = 2BIT_A + 2(z - BI - 1)$
$T^*_{i,j} + 2T^*_{2,j}$

(g) $I = 2 \sim M-N$, $J = N$

First half : $A_i = C_i = -1$,
$B_i = 2(1+z)$,
$D_i = 2BIT_A + 2(z - BI - 1)$
$T_{i,N,n} + 2T_{i,N-1,n}$

Second half : $A_j = -2$,
$B_j = 2(1+z)$,
$D_j = 2BIT_A + 2(z - BI - 1)$
$T^*_{i,N} + T^*_{i+1,N} + T^*_{i-1,N}$

(iv) Points on the Interface between Mold & Casting

* Before Air Gap Formation

(a) Points on Interface Parallel to y axis Separating Media A(left) and B(right)

First half : $A_i = -2K_A/(K_A + K_B)$,
$B_i = 2(z+1)$,
$C_i = -2K_B/(K_A + K_B)$
$D_i = T_{i,j-1,n} + 2(z-1)\,T_{i,j,n}$
$+ T_{i,j+1,n}$

Second half : $A_j = C_j = -1$,
$B_j = 2(z+1)$,
$D_j = 2K_A/(K_A + K_B)\,T^*_{i-1,j} +$
$2(z-1)\,T^*_{i,j} + 2K_B/(K_A +$
$K_B)\,T^*_{i+1,j}$

Here,

$$Z = \frac{C_1}{K_A + K_B}\left(\frac{K_A}{\alpha_A} + \frac{K_B}{\alpha_B}\right)$$

$$C_1 = (\triangle x)^2/\triangle t$$

(b) Points on Interface Parallel to x Separating Media A(below) and B(above)

First half : $A_i = C_i = -1$,
$B_i = 2(z-1)$,
$D_i = 2K_A/(K_A + K_B)\,T_{i,j-1,n}$
$+ 2(z-1)\,T_{i,j,n} + 2K_B$
$/(K_A + K_B)\,T_{i,j+1,n}$

Second half : $A_j = -2K_A/(K_A + K_B)$,
$B_j = 2(z+1)$,
$C_j = -2K_B/(K_A + K_B)$,
$D_j = T^*_{i-1,j} + 2(z-1)$

$T^*_{i,j} + T^*_{i+1,j}$

Here, the definition of Z is the same as above.

After Air Gap Formation

(a) $I = I4,\ J = J1+1$

First half : $A_i = -1,$

$B_i = 1 + 0.5z,$

$D_i = BIT_{i4,j1,n} + (0.5z - BI)$
$T_{i4,j1+1,n}$

Second half : $B_j = -BI,$

$C_j = BI + 0.5z,$

$D_j = T^*_{i4-j1+1} + (0.5z-1)$
$T^*_{i4,j1+1}$

(b) $I = I1+2 \sim I4-1,\ J = J1+1$

First half : $A_i = C_i = -1,$

$B_i = 2(1+z)$

$D_i = 2BIT_{i,j1,n} + 2(z - BI - 1)T_{i,j1+1,n} + 2T_{i,j1+2,n}$

Second half : $A_j = -2BI,$

$C_j = -2,$

$B_j = 2(1+BI+z),$

$D_j = T^*_{i-1,j1+1} + 2(z-1)$
$T^*_{i,j1+1} + T^*_{i+1,j1+1}$

(c) $I = I1+1,\ J = J1+1$

First half : $A_i = -BI,\ C_i = 1,\ B_1 = 1 + BI + z,\ D_i = BIT_{i1+1,j1,n} + (z - BI - 1)T_{i1+1,j1+1,n} + T_{i1+1,j1+2,n}$

Second half : $A_j = -BI,\ C_j = -1,\ B_i = 1 + BI + Z,$

$D_j = BIT^*_{i1,j1+1} + (z - BI - 1)$
$T^*_{i1+1,j1+1} + T^*_{i1+2,j1+1}$

(d) $I = I1+1,\ J = J1+2 \sim J2-1$

First half : $A_i = -2BI,$

$C_i = -2,$

$B_i = 2(1+BI+z),$

$D_i = T_{i1+1,J-1,n} + 2(Z-1)$
$T_{i1+1,j,n} + T_{i1+1,j+1,n}$

Second half : $A_j = C_j = -1,$

$B_j = 2(1+z),$

$D_j = 2BIT_{i1,j} + 2(z - BI - 1)$
$T^*_{i1+1,j} + 2T^*_{i1+2,j}$

(e) $I = I1+1,\ J = J2$

First half : $A_i = -BI,$

$C_i = -1,$

$B_i = 1 + BI + z,$

$D_i = T_{i1+1,j2-1,n} + (z - BI - 1)$
$T_{i1+1,j2,n} + BIT_{i1+1,j2+1,n}$

Second half : $A_j = -1,$

$C_j = -$

$B_j = 1 + BI + z,$

$D_j = BIT^*_{i1,j2} + (z - BI - 1)$
$T^*_{i1+1,j2} + T^*_{i1+2,j2}$

(f) $I = I1+2 \sim I3,\ J = J2$

First half : $A_i = C_i = -1,$

$B_i = 2(1+z),$

$D_i = 2T_{i,j2-1,n} + 2(z - BI - 1)$
$T_{i,j2,n} + 2BIT_{i,j2+1,n}$

Second half : $A_j = -2,$

$C_j = -2BI,$

$B_j = 2(1+BI+z)$

$D_j = -T^*_{i-1,j2} + 2(z-1)T^*_{i,j2}$
$+ T^*_{i+1,j2}$

(g) $I = I3+1,\ J = J2$

First half : $A_i = -(1+BI),$

$B_i = 1 + BI + 1.5z,$

$D_i = 2T_{i3+1,j2-1,n} + (1.5z - 2)T_{i3+1,j2,n}$

Second half : $A_j = -2,$

$B_j = 2 + 1.5z,$

$D_j = (1+BI)T_{i3,j2} + (1.5z - BI - 1)T_{i3+1,j2}$

(h) $I = I3,\ J = J2+1$

First half : $A_i = -1,\quad B_i = 1 + 0.5z,$

$D_i = BIT_{i3,j2,n} + (0.5z - BI)$
$T_{i3,j2+1,n}$

Second half : $A_j = -BI,\quad B_j = 0.5z + BI,$

$D_j = T^*_{i3-1,j2+1} + (0.5z - BI)$
$T^*_{i3,j2+1}$

(i) $I = I1+1 \sim I3-1,\ J = J2+1$

First half : $A_i = C_i = -1,$

$B_i = 2(1+z),$

$D_i = 2BIT_{i,j2,n} + 2(z - BI - 1)T_{i,j2+1,n} + 2T_{i,j2+2,n}$

Second half : $A_j = -2BI,$

$C_j = -2,$

$B_j = 2(1+BI+z),$

$D_j = T^*_{i-1,j2+1} + 2(z-1)$
$T^*_{i,j2+1} + T^*_{i+1,j2+1}$

(j) $I = I1,\ J = J2+1$

First half : $A_i = -2,$
$C_i = -(1+BI),$
$B_i = 3+BI+3z,$
$D_i = (1+BI)T_{i1,j2,n} + (3z-3$
$-BI)T_{i1,j2+1,n} + 2T_{i1,j2+2,n}$

Second half : $A_j = -(1+BI),$
$C_j = -2,$
$B_j = 3+BI+3z,$
$D_j = 2T_{i1-1,j2+1} + (3z-BI-3)$
$T_{i1,j2+1} + (1+BI)$
$T_{i1+1,j2+1}$

(k) $I = I1,\ J = J1+1 \sim J2$

First half : $A_i = -2,$
$C_i = -2BI,$
$B_i = 2(1+z+BI),$
$D_i = T_{i1,j-1,n} + 2(z-1) +$
$T_{i1,j+1,n}$

Second half : $A_j = C_j = -1,$
$B_j = 2(z+1),$
$D_j = 2T^*_{i1-1,j} + 2(z-BI-1)$
$T^*_{i1,j} + 2BI\,T^*_{i1+1,j}$

(l) $I = I1,\ J = J1$

First half : $A_i = -2,$
$C_i = -(1+BI),$
$B_i = 3z+3+BI,$
$D_i = 2T_{i1,j1-1,n} + (3z-3-$
$BI)T_{i1,j1,n} + (1+BI)$
$T_{i1,j1+1,n}$

Second half : $A_j = -2,$
$C_j = -(1+BI),$
$B_j = 3z+BI+3,$
$D_j = 2T^*_{i1-1,j1} + (3z-3-BI)$
$j\quad T^*_{i1,j1} + (1+BI)T^*_{i1+1,j1}$

(m) $I = I1+1 \sim I4,\ J = J1$

First half : $A_i = C_i = -1,$
$B_i = 2(z+1),$
$D_i = 2T_{i,j1-1,n} + 2(z-BI-1)$
$T_{i,j1,n} + 2BI\,T_{i,j1+1,n}$

Second half : $A_j = -2,$
$C_j = -2BI,$
$B_j = 2(z+BI+1),$
$D_j = T^*_{i-1,j1} + 2(z-1)T^*_{i,j1} +$
$T^*_{i+1,j1}$

(n) $I = I4+1,\ J = J1$

First half : $A_i = -(1+BI),$
$B_i = (1.5z+BI+1),$
$D_i = 2T_{i4+1,j1-1,n} + (1.5z-2)$
$T_{i4+1,j1,n}$

Second half : $A_j = -2,$
$B_j = 1.5z+2,$
$D_j = (1+BI)T^*_{i4,j1} + (1.5z$
$-BI-1)T^*_{i4+1,j}$

## II-3. CALCULATION

(1) Data

The data used in this calculation are the following;

i) Cast iron

Density $= 7.22\ g/cm^3$

Specific Heat $Cp = 0.0222 + 1.5432 \times 10^{-5}\ t$

Heat Conductivity $K = 0.1605 - 6.039 \times 10^{-5}\ t$ (12)

ii) Aluminum

a) Liquid State

Density

$p = 2.537 - 0.256 \times 10^{-3} t$

Specific Heat

$Cp = 0.2594$ – (700.1°C–)

$Cp = 4.893 - 0.2317\,(t-680.1)$

(680.1 – 700.1°C)

$Cp = 0.2854 + 0.2304\,(t-660.1)$

(66.1 – 680.1°C)

Thermal Conductivity

$K = 0.2597 - 6.880 \times 10^{-5}\ t$ (17)

b) Solid State

Density

$p = 2.757 - 0.301 \times 10^{-3} t$

Specific Heat

$Cp = 0.2130 + 0.1097 \times 10^{-3} t$

Thermal Conductivity

$K = 0.4153 + 8.0989 \times 10^{-5} t - 1.6489 \times 10^{-7} t^2$

iii) The heat transfer coefficient at the interface after the air-gap formation, hi (15)

$hi = Kg/Wg + R0$

$R = 1/(1/Rc + 1/Rm - 1/Ro)$

$\theta = 0.04\,(Tg/100)^3$

$Tg = (Tc + Tm)/2$

Here,

Kg; heat conductivity of air (17)

$$5.33 \times 10^{-5} \times \left(\frac{(273 + 125)}{(T_C + 125)} \times \frac{T_C}{273}\right)^{3/2}$$

Wg ; thickness of air-gap 0.03 cm

Rc ; radiation coefficient of casting $2.042 \times 10^{-5}$ $Cal/cm^2$ sec $K^4$

Rm ; radiation coefficient of mold $1.089 \times 10^{-4}$

Ro ; radiation coefficient of black body $1.361 \times 10^{-4}$

iv) Air Gap Formation Time (in Seconds) (10)

| Volume Ratio | 2 | 3 | 4 | 6 |
|---|---|---|---|---|
| Time | 20 | 15 | 13 | 11.5 |

(2) Casting & Mold Size

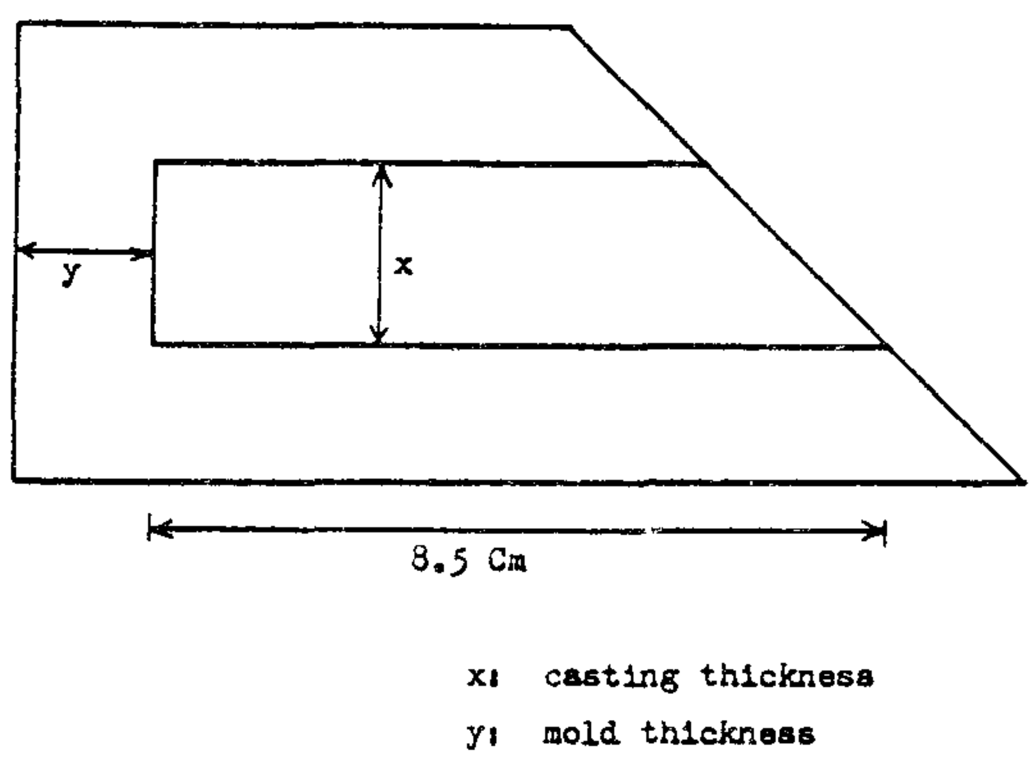


Figure 4. Mold & Casting Size used for Calculation

(3) Execution

Time increment $\Delta t = 0.15$ sec

Space increment $\Delta x (= \Delta y) = 0.15$ cm

(When the mold wall was thick, either 0.20 or 0.25 cm was used to reduce the total number of grid points.)

Table 1. Mold Sizes Calculated According to Mold Ratio (in cm)

| | | Volume Ratio (V. of mold/V. of casting) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Casting Thickness in cm | 1.5 | 0.6 | 1.2 | 1.65 | 2.2 | 2.6 | 3.0 |
| | 2.0 | 0.85 | 1.6 | 2.2 | 2.6 | 3.2 | 3.6 |

All thermal properties in a certain grid point are newly obtained at every time-step by applying the temperature of the moment. What it is time for the air-gap to form, a row of new nodal points is needed along the interface. So, new nodal points are added according to this and the temperature at the interface just before the air-gap formation are given to the newly made grid points.

## III. RESULTS & DISCUSSION

(1) Calculation with Simple Assumptions

Shown in figure 5 are the calculation results with the assumptions that the temperature at the mold surface is constant and that the air-gap does not form at the interface.

According to this results, the time required for a casting to solidify increases with the volume of the mold. This is obviously not true. In reality, a mold is the immediate heatsink and with a larger volume, it has a bigger heat capacity enabling it to absorb the superheat & latent heat of the casting much faster. Therefore, it is anticipated that the solidification time will be reduced abruptly with a larger mold volume (i.e., a thicker mold wall).

It can be considered that the incorrect results above are mainly caused by the assumption that the temperature at the mold surface was constant. The physical meaning of the assumption is that the heat from the casting should be transfered into the atmosphere at the moment it reaches the outer mold surface. This is because a temperature change occures when there is any difference between the two rates; the heat transfer rate from the casting to the surface and that from the surface into the atmosphere. This in turn means that the heat transfer coefficient at the mold surface is infinite. Therefore, with smaller mold thickness (smaller mold ratio), the faster the heat from

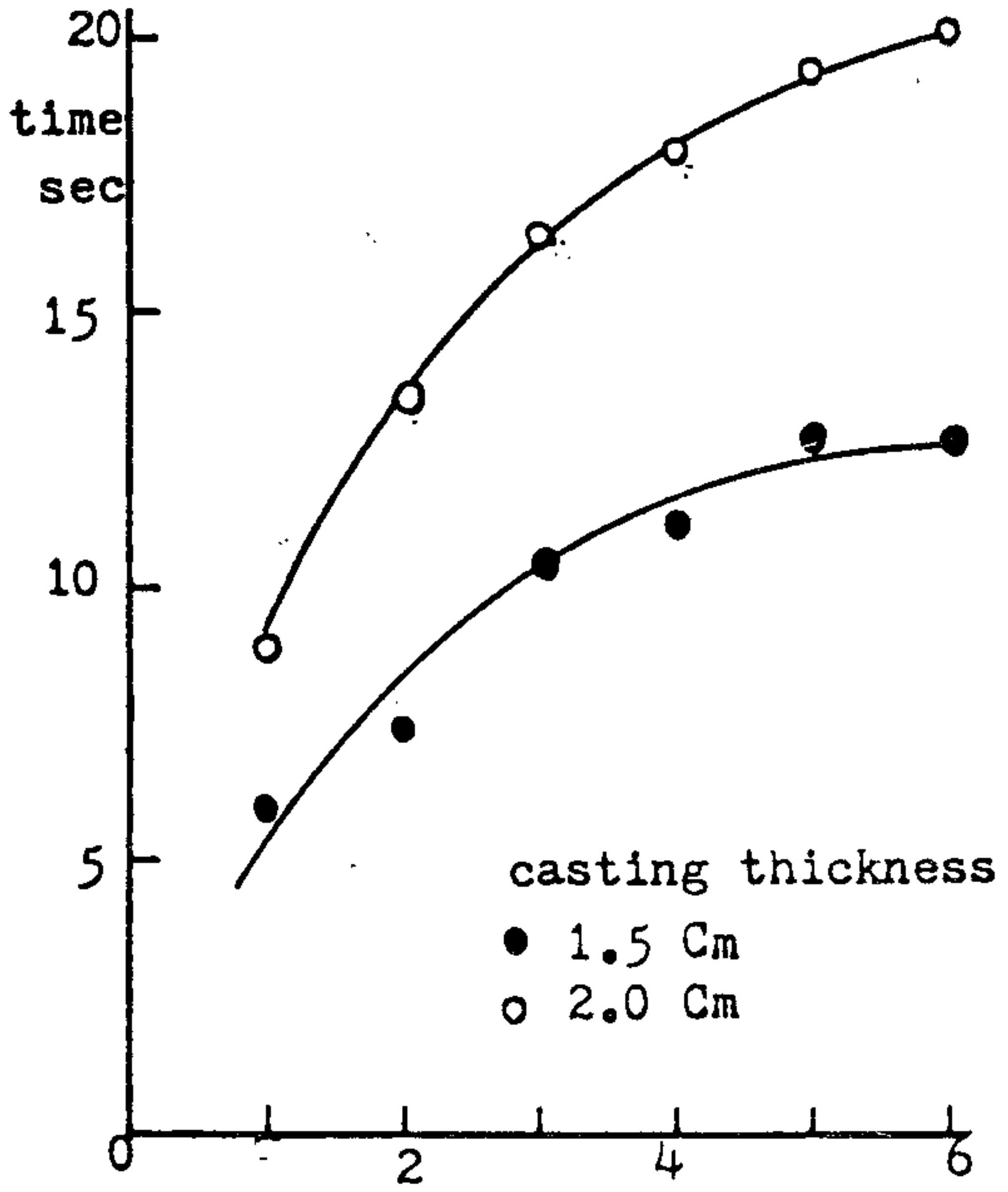


Figure 5. Relationship between mold ratio & solidification time according to the simple assumptions

the interior can be transferred into the atmosphere. This fact seems to cause the incorrect results shown in figure 5. So, Calculating with those assumptions results in a bigger error in the lesser mold-ratio range, while the error caused by the assumption of no air-gap formation seems to be constant without regard to mold ratio.

When some data, except for the solidification time, are needed (such as the direction of solidification, the location of hot spots, and the volume of shrinkage voids, etc.), calculating with the simple assumptions seems to be efficient. As an example, the process of solidification obtained with simple assumptions is plotted in figure 6.

Though the figures representing time (in second) in figure 6 are much different from those of the real situation, the aspect of the solidification process seems to be very close to reality. Therefore, when analyzing a solidification process of some complicated shaped casting, such data mentioned above can be obtained without routine calculation by these simple assumptions.

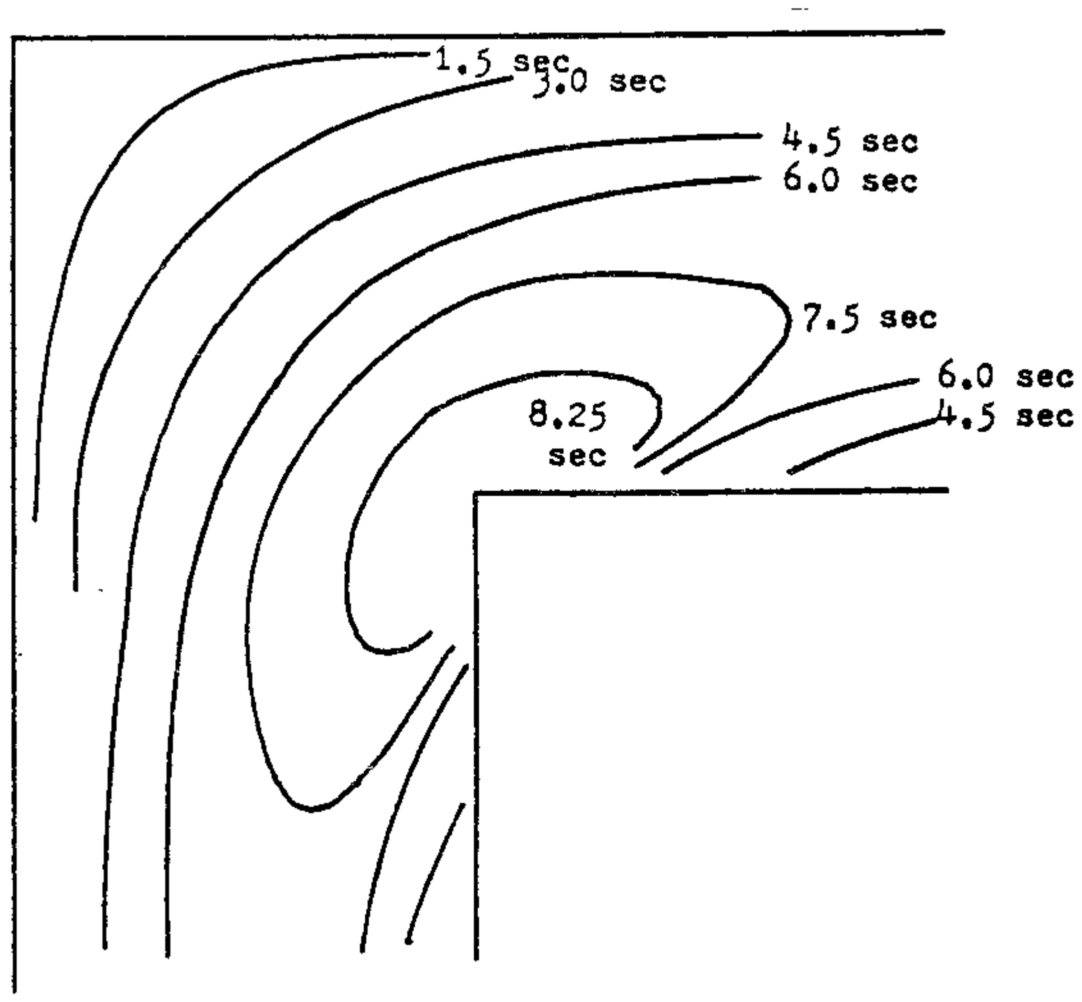


Figure 6. Progression of End-of-Freeze Contour (Thickness = 1.5 cm, mold ratio=1)

(2) Calculation with Modified Assumptions

The application of the IAD method to the mold surface (convection), and to the interface (air-gap, conduction & radiation) was attempted with the results shown in figure 7.

Theresults shows a similarity to those M.I. Thamban[14] obtained the experimenting wth 1-dimensional casting, that is, the abrupt decrease of the solidification time with the mold ratio. Similarity is also shown in the results obtained by A.I. Veynik[16] with Al-alloy.

From this fact, it can be concluded that calculating with the two factors can be considered a more realistic approach to the problem.

To study the effect of the air-gap on heat transfer, figure 8 is obtained by plotting the temperatures near the interface when a steady state is reached. According

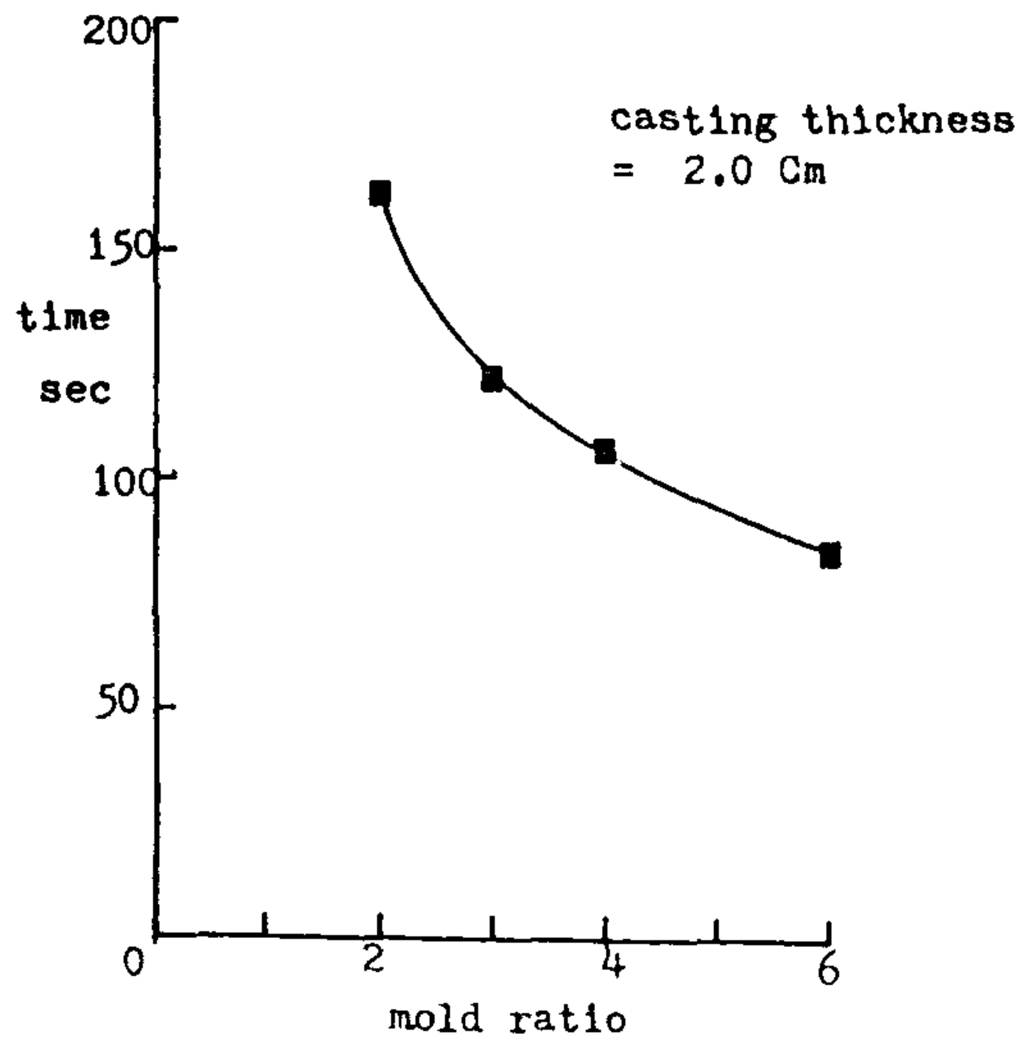


Figure 7. Solidification time calculated according to the modified conditions

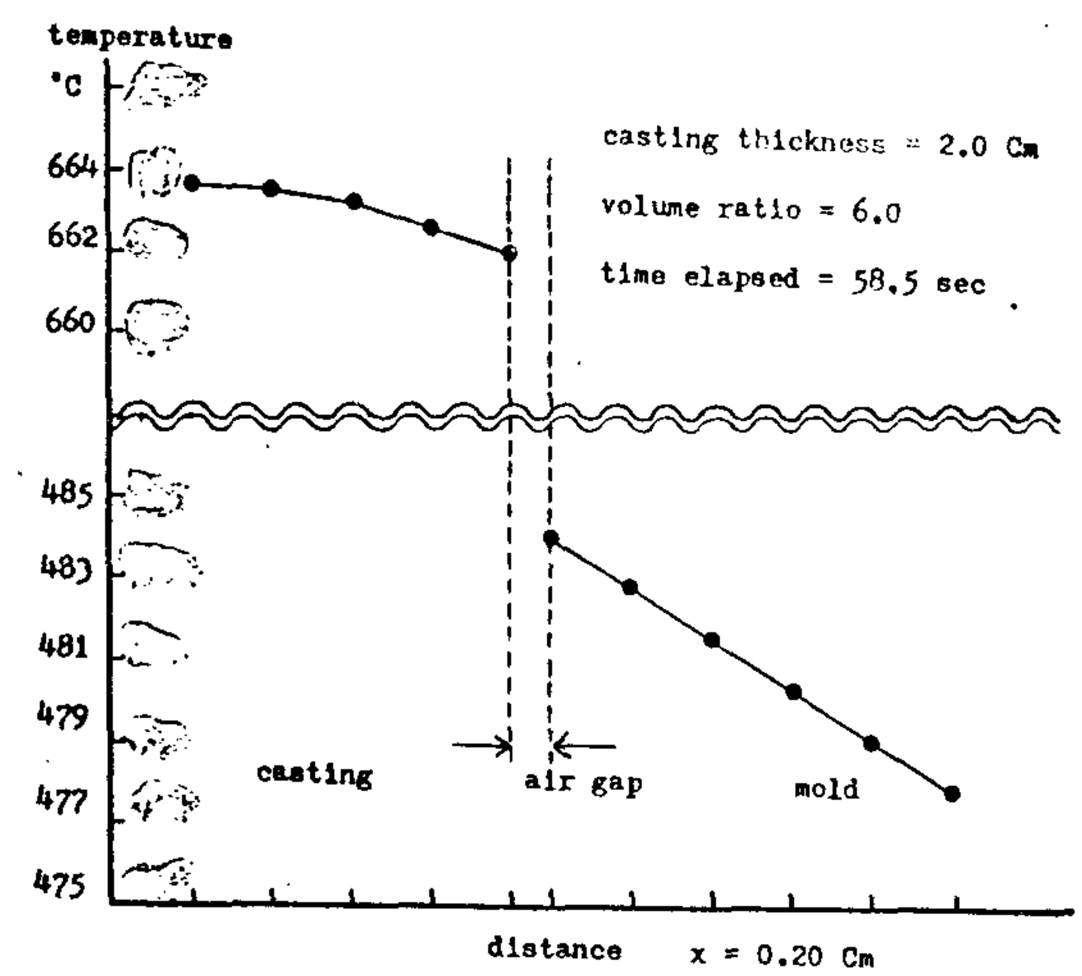


Figure 8. Temperature distribution on both the mold & the casting sides of air-gap

to figure 8, the temperature gradient shows a quadratic curve near the center of the casting, while showing a straight line in the mold. From the great temperature difference between the two sides of the air-gap, it is shown that the air-gap behaves like an insulation on the heat transfer at the mold/casting interface.

## IV. CONCLUSIONS

The conclusions obtained through this research are the following:

1. The IAD method can be applied to the mold surface and mold/casting interface without being restricted by the tability & convergency conditions.
2. When it was assumed that the temperature at the mold surface was constant and that there was no air-gap at the interface, the calculation result was shown to be much different from reality. Especially, that phenomenon was proven to be greater in the small mold-ratio range (1-4).
3. The results, obtained through taking these two factors (convection at the mold surface & air-gap formation at the interface) into consideration, showed a similarity with those obtained by M.I. Thamban and V.I. Veynik. Taking these things into consideration, the calculation with the two factors can be considered a more realistic approach to the problem.
4. After the air-gap had formed, the temperature distribution near the interface showed that the air-gap behaved as a poor heat conductor.

## REFERENCES

1. R.D. Pehlke et. al., "Numerical Simulation of Solidification" AFS Cast Metals Research Journal, December 1970.
2. J.T. Berry and R.D. Pehlke, "Progress Report on the Computer-Aided Design System Project" AFS Transactions 80-103.
3. A. Jeyarajan and R.D. Pehlke, "Application of Computer-Aided Design to a Steel Wheel Casting" AFS Transactions 78-157.
4. R.B. Weatherwax and O.K. Riegger, "Computer-Aided Solidification Study of a Die-Cast Aluminum Piston" AFS Transactions 77-103.
5. M.J. Kirt and R.D. Pehlke, "Determination of Material Thermal Properties Using Computer Techniques" AFS Cast Metals Research Journal, September 1973.
6. R.D. Pehlke et. al., "Computer Simulation of

Solidification of a Casting with a Chill" AFS Transactions 76-143.

7. Y. Ebisu, "Computer Simulation on the Macro-structures in Centrifugal Castings" AFS Transactions, 77-35.
8. R.D. Pehlke et. al., "Numerical Simulation of Casting Solidification" AFS Transactions, 73-122.
9. G.P. Reddy, "Design at the External Corners of V. Junctions Using Numerical Techniques" AFS Transactions, 77-14.
10. M.I. Thamban & V. Panchanathan, "Numerical Simulation of Solidification of Aluminum Alloys in Cast Iron Molds" AFS Transactions, 80-53.
11. A.E. Umble, "Computer Simulation for Determining Chilling Practice on Cast Steel Rolls" AFS Transactions, 78-26.
12. R.C. Sun, "Simulation and Study of Surface Conductance for Heat Flow in the Early Stage of Casting" AFS Cast Metal Research Journal, September 1970.
13. R.D. Pehlke & R.A. Flinn et, al., "Computerized Design Systems for Castings" AFS Project Report.
14. M.I. Thamban, S. Gopala Krishnan & V. Panchanathan, "Thermal Behavior of Cast Iron Molds with Long Freezing Range Aluminum Alloys" AFS Transactions 79-05.
15. A.I. Veynik, "Theory of Special Casting Methods" A.S.M.E. (1960) pp. 50-53, 67-72, 306-307.
16. A.I. Veynik, "Thermodynamics for the Foundryman" London, Maclaren, 1968, p.53.
17. National Research Council of the U.S.A., "International Critical Tables" McGraw-Hill Book Co., N.Y., (1929), Volume V p. 213, 214, 220, 230.
18. R.D. Pehlke, E. Marrone & J.O. Wilkes, "Computer Simulation of Solidification" American Foundrymen's Society, Monograph, 1976.
19. D.R. Croft & D.G. Lilley, "Heat Transfer Calculations Using Finite Difference Equations" Applied Science Publishers LTD, London, 1977, p. 227.

**The 51st. International Foundry Congress** is to be held in Lisbon from the 16th. to 20th. June 1984 and is organized by the Portuguese Foundry Association under the auspices of the International Committee of Foundry Technical Associations.
We are looking forward to welcoming foundrymen from all over the world at 51st. IFC and showing them significant aspects of the industry and some of the varied landscapes of our country.
Portugal is one of the oldest nations in Europe, with a rich historical, cultural and humanistic heritage.
The organizers of the 51st. IFC are particularly concerned with those factors which determine the human situation in the increasingly automated technological context and have chosen **Foundry, Informatic and Humanism** as the theme of this Congress.
The importance and human relevance of this topic, together with the high scientific and technical level of the papers should guarantee interesting sessions for all participants.
As a diversification to the technical work of the Congress visits to the modern plants across the country, as well as a number of events of cultural and social nature are arranged.
We have also planned a full ladies programme and various post-congress tours including a visit to the GIFA, Düsseldorf, and we expect participants to take home with them the warmest memories of their stay.