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# Computer Simulation of Solidification Process in the Gravity Die Casting

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## Abstract

A basic three dimensional thermal model has been developed to simulate the solidification sequence for gravity die casting process. The finite difference method was used to analyze the solidification process during all the casting cycles. The prediction of die temperature in the quasi-steady state was analyzed by the boundary element method. The influence of die cooling on the heat flow in the cast/mold system was also investigated. Predictions of the computer simulation on temperature profiles and location of shrinkage defects were in good agreement with those observed in experimental die castings. Models of computer simulation which is developed by this work can be useful for the design and process control of die casting.

## Auszug

Zu simulieren die Erstarrungsequenz vom kokillenguss ist ein grundlegendes Dreidimension-Wärmemodell angenomen worden.

Das Finite-Differenz-Verfahren wurde zu modellieren das Erstarrung-sprozess während des erste Übergangszustandes benutzt.

Die Voraussage von der Temperatur im quasi-stationäre Zustand wurde durch das Grenze-Elemente-Verfahren ausgeführt.

Der Einfluss vom Abkühlungsystem auf dem Erstarrungsprozess wurde auch untersucht.

Temperatursverteilung von der Kokille und Lage des Schwindungsfehlers vom Guss, vorausgesagt von der Computer-Simulation während des Giessprozesses, übereingekommen mit dem Resultat gebeobacht im Versuchguss. Das Wärmemodell werde auf Kokillengestaltung und Prozesssteuerung vom kokillengiessverfahren angewendet.

## Résumé

Pour analyser le processus de solidification dans le moule de gravité, le modele de transmission de la chaleur á trois dimensions est employé. pour former un modele sur le processus de solidification au debut de l'etat transitoire, une methode de difference fini est utilisé. La prevision de la temperature du molele á l'etat de guasi-station est realisé par utilisation de la methode de l'ements limités.

Les influences du system de refroidisment du moule sur le processus de solidification sont aussi étudiés.

Les résuetats de lasimulation de l'ordinateur sur le profil de la temperature dans le moule et l'endroits des defauts de contration dans le fontesont bien coincidès aux résuetats experimentaux par le processus cyclique du moulage.

Ce modele donne beaucoup d'applications sur le plan du moule etlecontrole des processus pour moulage.

## 1. Introduction

In permanent mold casting, active mold cooling systems are frequently employed with water cooling to remove the heat of the solidifying metal. Thermal modeling is an important techniaue in designing of mold, for improving the productivity of the process, for avoiding the formation of casting defects, for avoiding the formation of control of mold temperatures, and for increasing mechanical properties through regulating solidification rates. Since permanent molds are often complex, thermal modeling is not simple in three dimensional shapes. Although heat flow designs in molds are commonly done by trial and error, this can be expensive in terms of lost time and mold modification costs. There is then a considerable potential for thermal modeling as a tool in mold or die design. Several studies of theoretical aspects of heat flow in the metal mold have been reported, including the work of Wallace et al.[1], who investigated aspects of heat transfer in the die casting process, Caswell and Lorentzen[2], who described a computer method specifically for die casting applications.

Recently, several studies using computer simulation of die casting process have been reported, including the work by Weatherwax et al.[3], who simulated three dimensional solidification problem of a die cast aluminum piston by using the FEM, Grant[4], who applied thermal modeling technique to a permanent mold casting cycle for improving the productivity of the process by using the two dimensional thermal modeling based on the FDM, and Rigger[5], who adopted the FEM to model the three dimensional die casting process for eliminating macro porosity due to shrinkage. Ikeda et al.[6] also studied a thermal analysis method to predict temperature distributions in a die for aluminum alloy castings. Recently, Hong et al.[7] applied thermal modeling techniaue to a permanent mold casting for designing the cooling channel system by using the boundary element method.

In this study, a basic three dimensional thermal model has been developed to simulate the solidification sequence for gravity die casting. The finite difference method was used to model the solidification process during all the casting cycles. Prediction of die temperature in the quasi-steady state was analyzed by the boundary element method.

The effects of water cooling system on the formation of shrinkage defects are also simulated and its results are compared with the experimental castings.

## 2. Experimental Procedures

A simple shape of cast iron mold was used for aluminum alloy castings(Al–7% Si–0.3% Mg). The "T" shape castings were cast in a single cavity mold by the gravity casting process.

Fig. 1 shows a cross section of the mold and casting system. The numbers 1 through 3 indicate the location of thermocouples in the mold, and the letters A and B indicate the position of water cooling channels. A complete casting cycle is of 240 seconds and it consists of a 120 second closed mold period and a 120 second open mold period.

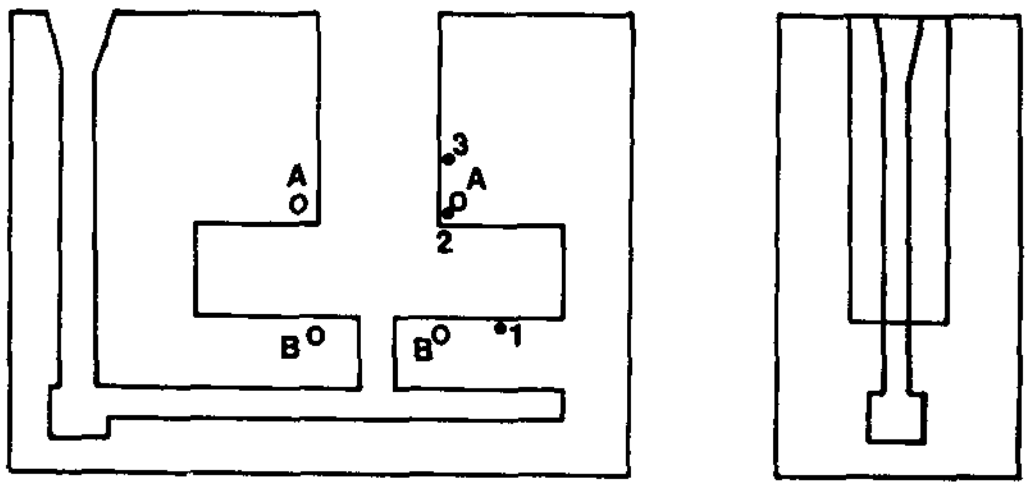


Fig. 1 Mold cross section for experimental casting.

## 3. Numerical Modeling

### 3-1. Finite differnece model for solidification analysis during cyclic casting process

A three dimensional thermal model based on the finite difference method was used to simulate the solidification process of the casting/mold system. The closed and open mold aspects of the complete casting cycle were simulated by adjusting the boundary conditions to account for the characteristics peculiar to each of the two parts of the cycle.

An instant fill of the casting was assumed at the start of the closed mold period. During the closed mold period, the solidification analysis and the prediction of shrinkage cavity of the casting are analyzed by the FDM. During the open mold period, the casting was removed from the simulation model, and the mold cavity was allowed to exchange heat with the environment.

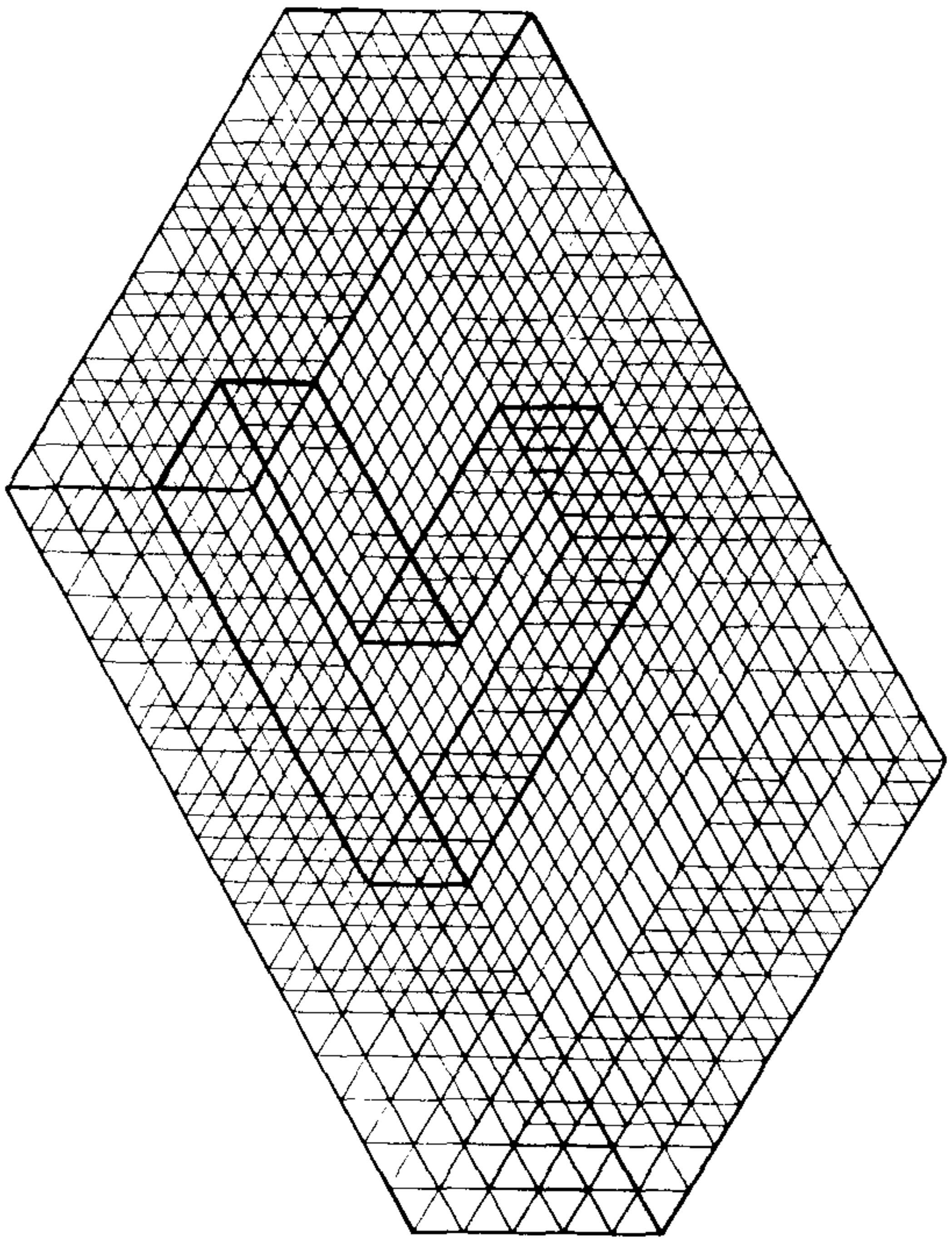


Fig. 2 Finite difference model for three dimensional analysis.

A finite difference nodes for three dimensional analysis are schematically shown in Fig. 2.

### 3-2. Boundary element model for heat flow analysis in mold during the quasi-steady state.

Cyclic average mold temperatures are raised up to the quasi-steady state during the starting transient. After the transient state, the mold temperatures oscillate about their respective quasi-steady state values, through each casting cycle, as shown in Fig. 3. This cyclic variation during the steady operation corresponds to actual production conditions. The modeling of this period is more important and practical rather than that of the starting transient. Several cycles may be necessary for average mold temperature to reach their steady value. To control the average mold temperatures during the quasi

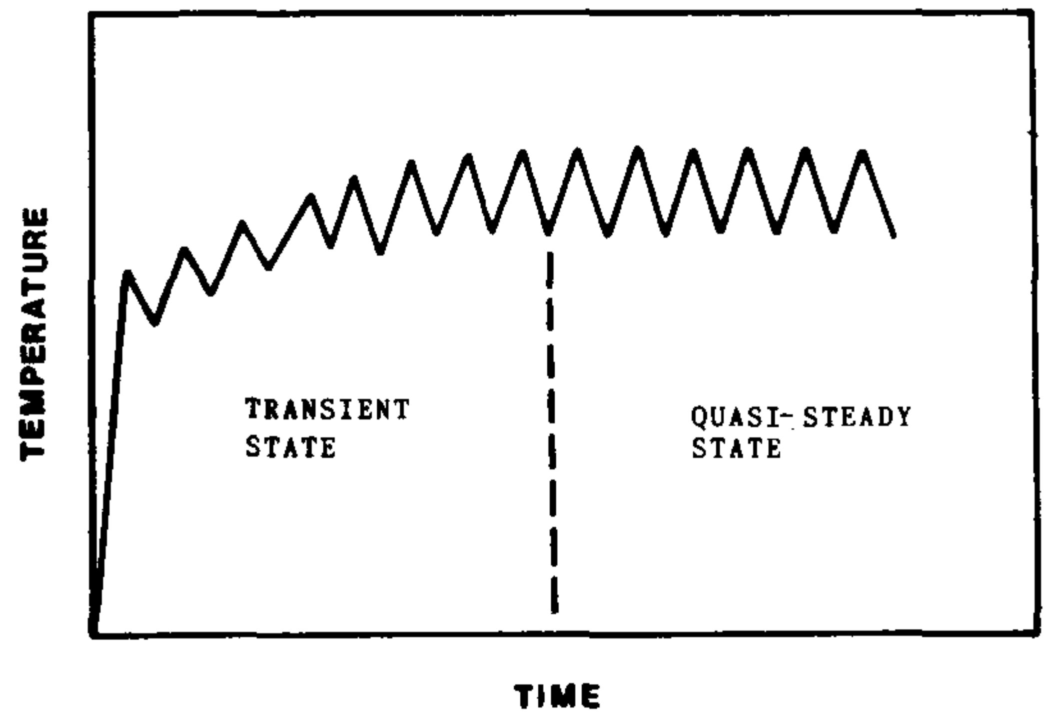


Fig. 3 Temperature variation in a metal mold during cyclic process of a gravity die casting.

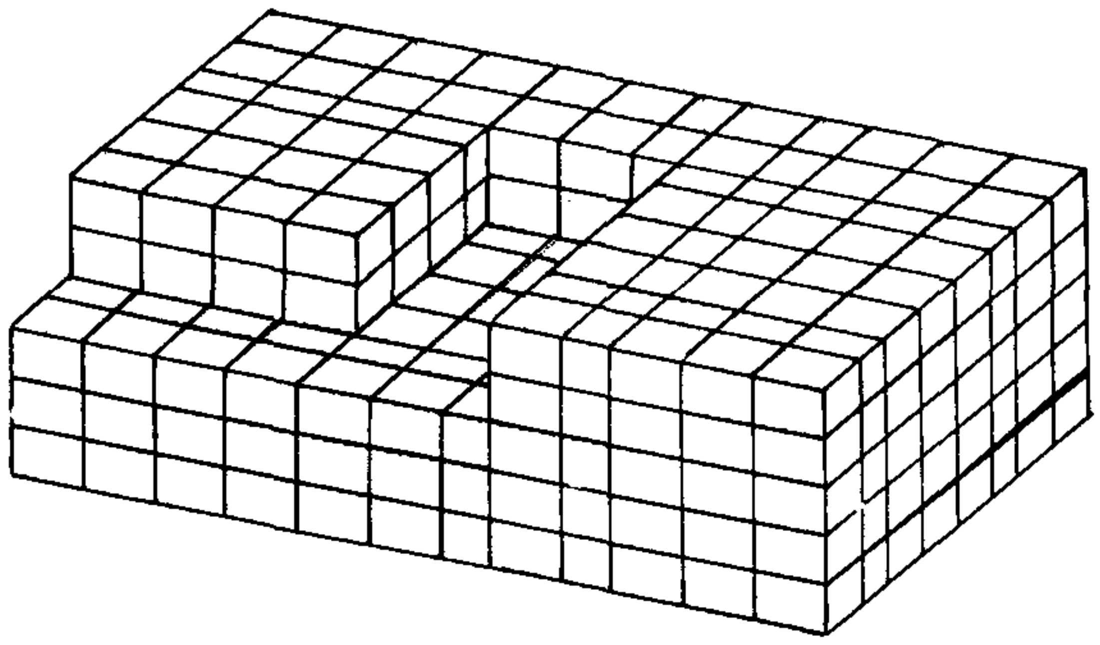


Fig. 4 Boundary elements discretization.

-steady state is important for improving the productivity of the process, for avoiding the formation of shrinkage cavity and for prolonging mold life. In the present study, the boundary element method was adopted for thermal modeling of permanent mold during the quasi-steady state. The effect of water cooling system on the temperature distributions in the mold region are also investigated. A boundary element discretization for three dimensional heat flow analysis is schematically shown in Fig. 4.

## 4. Results and Discussion

### 4-1. Solidification analysis and prediction of shrinkage cavity by the FDM

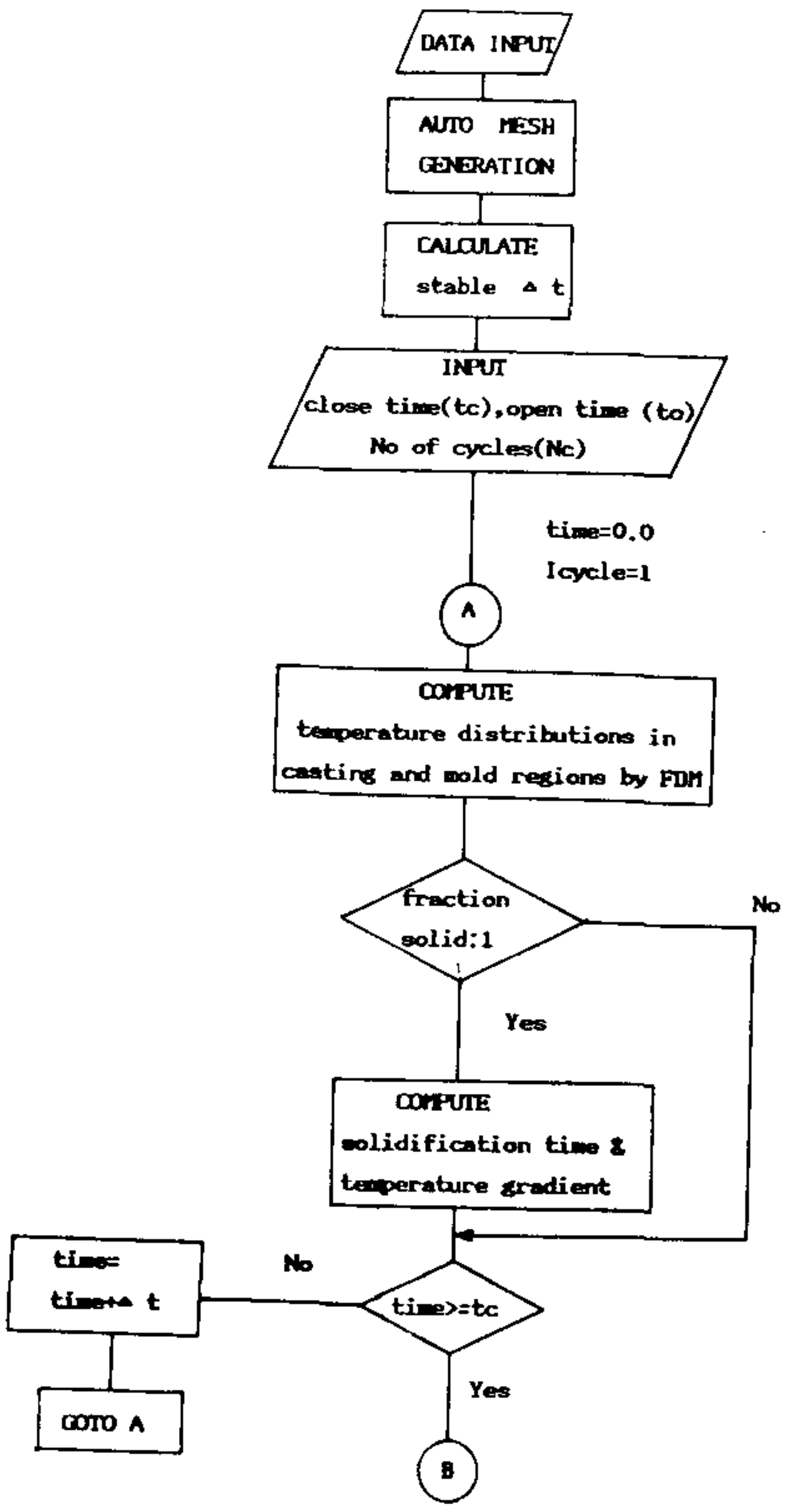
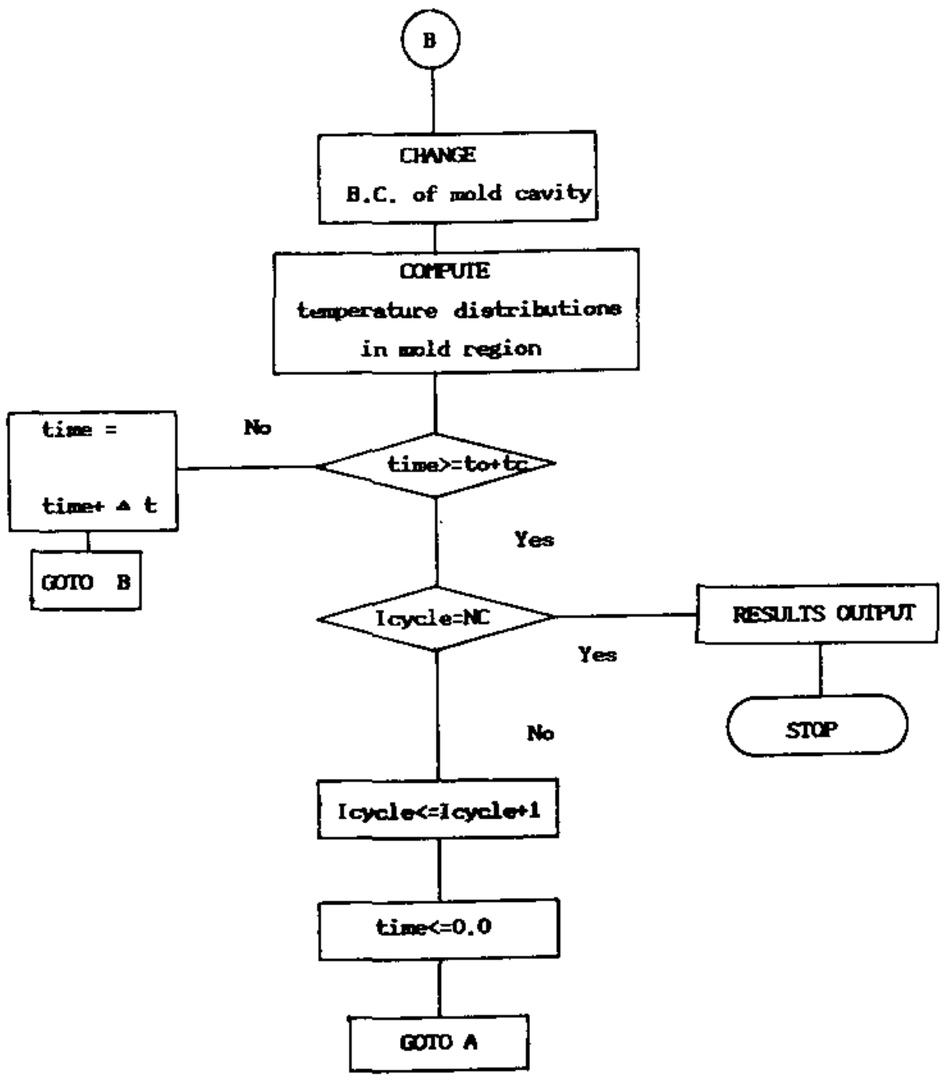
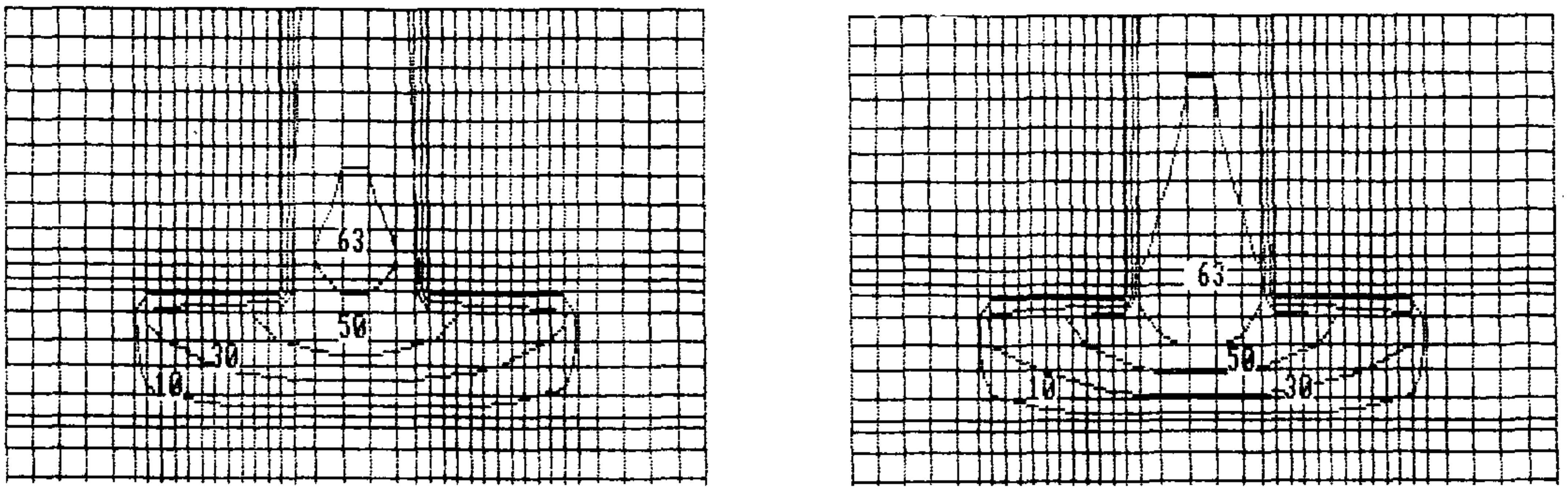


Fig. 5 Flow diagram for heat flow analysis.

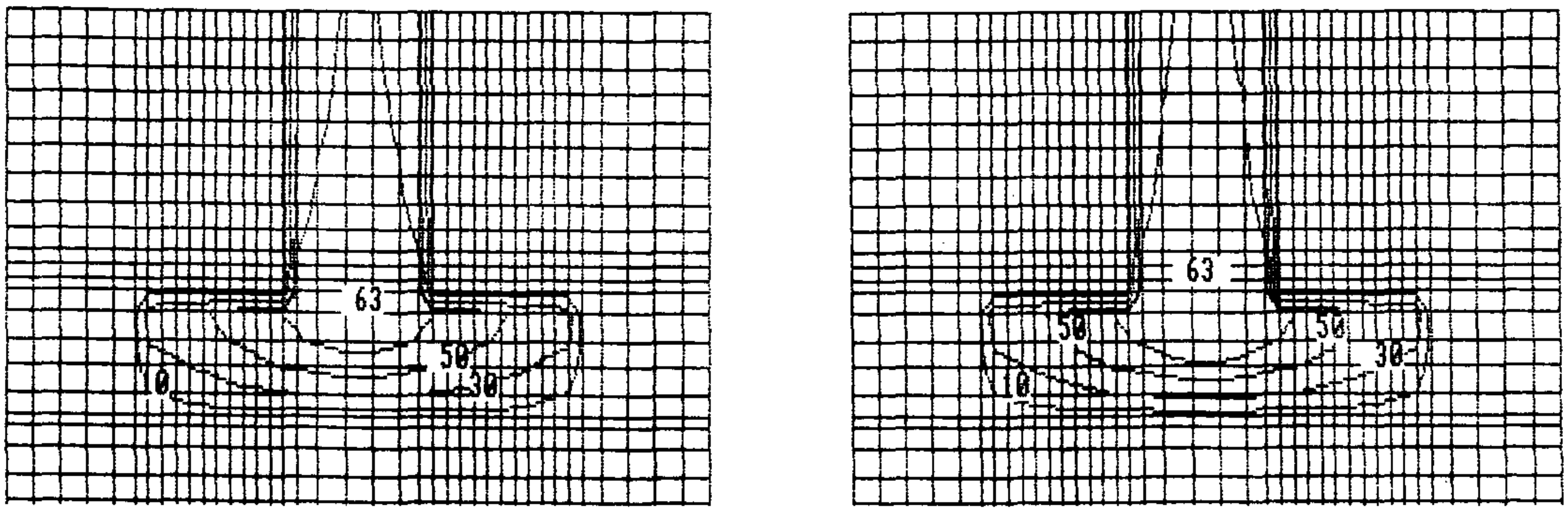


continued from Fig. 5.

Solidification analysis of casting during the closed mold period and heat flow analysis of mold during the open mold period were carried out through each casting cycle. A flow diagram for this analysis is shown schematically in Fig. 5 Two prediction parameters, solidification time and temperature gradient, are adopted to pred-



CYCLE 1 CYCLE 3



CYCLE 5 CYCLE 7

Fig. 6 Solidification time contour lines for without cooling channels.

ict the formation of shrinkage cavity of casting.

Fig. 6 shows the contour lines of solidification time in casting cycle 1 through cycle 8, for without cooling channels. It can be seen from figures that the region enclosed by solidification time contour moves from the center of riser to the center of casting by cycling.

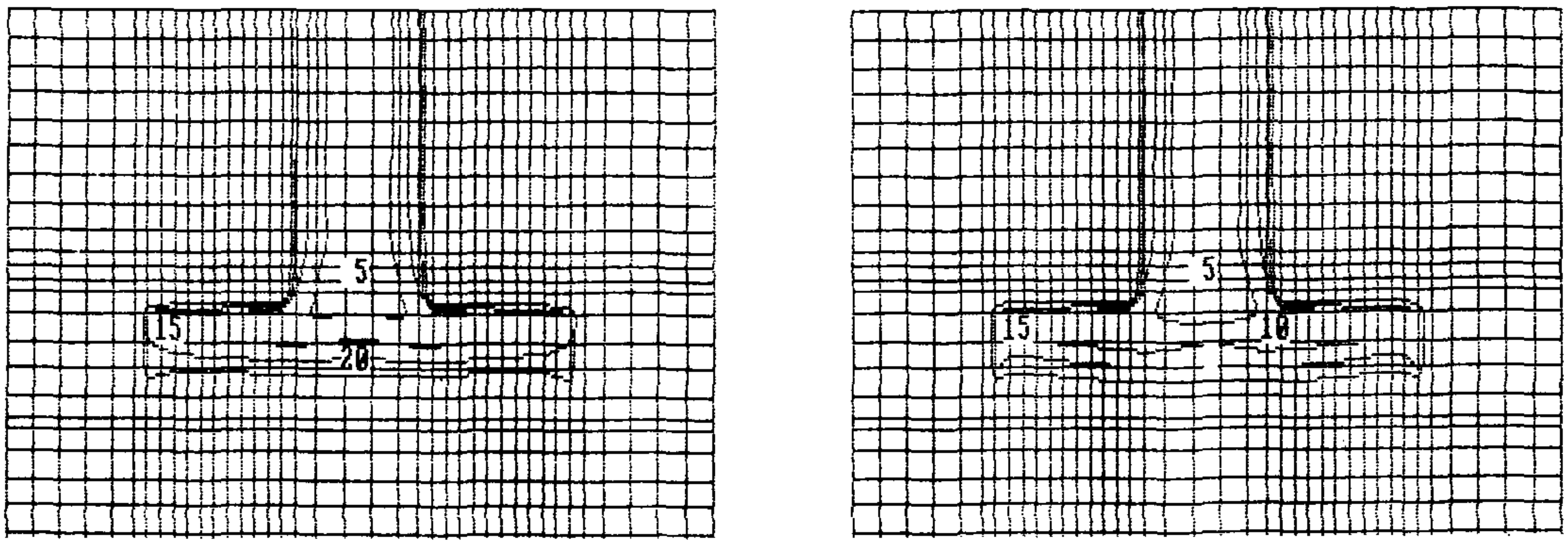
Fig. 7 shows temperature gradient contour lines. The loop size enclosed by temperature gradient contour of 5℃/cm increases by cycling, and its center moves toward the casting region.

Fig. 8 shows the results of experimental castings, and the area of shrinkage cavity spreads out widely by cycling. It is seen from figures that combined use of prediction parameters, solidification time and temperature gradient can predict the formation of shrinkage cavities in castings. The effects of cooling channels on the solidification patterns are shown in Fig. 9 and 10, for casting cycle 1 through cycle 6 And the results of experimental castings are also shown in Fig. 11.

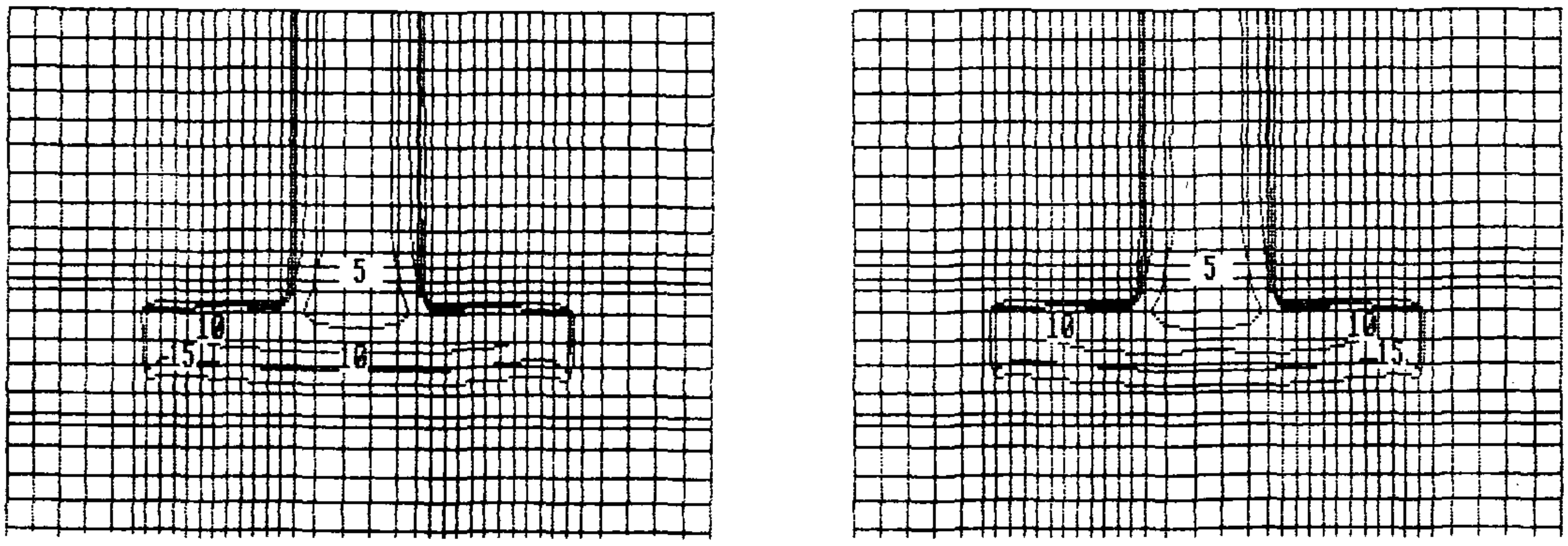
In this case it is found that solidification patterns and shrinkage cavities are not affected by cycling.

### 4-2. Heat flow analysis in mold cavity by the BEM.

Measured temperature profiles for several nodes in mold are shown in Fig. 12 (a) & (b) ; (a) for without water cooling and (b) for with water cooling channels. It can be shown from figure 12 that temperature profiles are not changed by the use of water cooling channel. However, it requires 7 to 8 casting cycles for the average mold temperature to reach their



CYCLE 1 CYCLE 3



CYCLE 5 CYCLE 7

Fig. 7 Temperature gradient contour lines for without cooling channels.

quasi-steady state values for without water cooling channels. It is, thus, sufficient to treat the thermal modeling of heat flow in a mold as a steady state problem.

During the quasi-steady state, the mold temperature was simulated by the BEM, and the results are in good agreement with the measured values, as shown in Fig. 12.

Fig. 13 (a) and (b) demonstrate the calculated temperature distributions of section A-A inside the mold region by the BEM ; (a) for without water cooling, and (b) for with water cooling channels. The boundary condition of the cast/mold interface treated as natural boundary.

The heat flux, q, at the cast/mold interface, must be estimated for heat flow analysis by the BEM. The following equation is used for evaluation of q approximately.

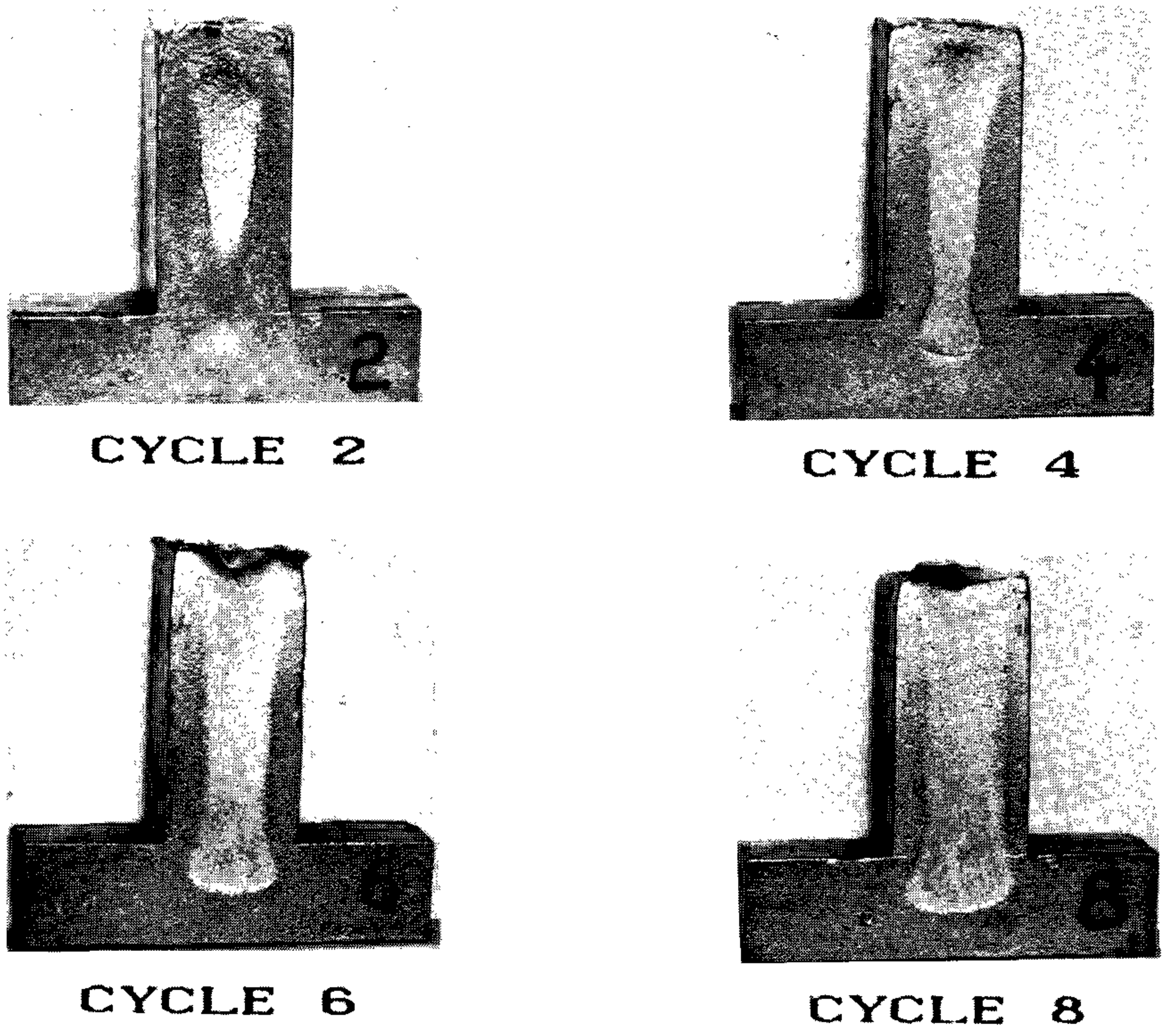
$$q = Vc \cdot \rho\{C(Tp - Te) + L/(Ac \cdot tcycle)\}$$

Where Vc is the volume of casting, Ac the total surface area of the casting, tcycle the length of one casting cycle, Tp the pouring temperature, and Te the average temperature of the casting at time of ejecting, respectively. In this case q is estimated approximately at 1.49 cal/cm$^2$.sec.

As a transient heat flow problem, the mold temperature distributions can also be simulated by the FDM.

Fig. 14(a) and (b) demonstrate the results calculated 30 seconds after pouring when the mold average temperature reach to its quasi-steady state values ; (a) for without water cooling, and (b) for with water cooling channels.

As shown in figures, the results being simulated by the BEM are relatively in good agreement



CYCLE 2 CYCLE 4

CYCLE 6 CYCLE 8

Fig. 8 Results of experimental castings for without cooling channels.

with those obtained by the transient FDM. It was found that the boundary element method gives a considerable saving in data preparation and CPU times, especially in complex, three dimensional geometries. Even though the approximation in this model seems to be rough, the model has a considerable potential for designing of cooling or heating system in a die or permanent mold.

## 5. Conclusion

A basic three dimensional thermal model is presented for simulation of solidification and heat flow in the gravity die casting process.

The finite difference method was used to analyze the solidification profile and to predict shrinkage cavity formation in the starting transient and quasi-steady state. The model which is developed in this study is capable of controling solidification process and preventing shrinkage cavity formation in the casting.

In the quasi-steady state, heat flow in a die or mold was simulated by the boundary element method. It was found that the boundary element method gives a considerable potential for designing of cooling systems in a die or permanent mold because of its advantages of simplicity in numerical formulation, simple data preparation and small CPU times compared with the FDM or FEM.

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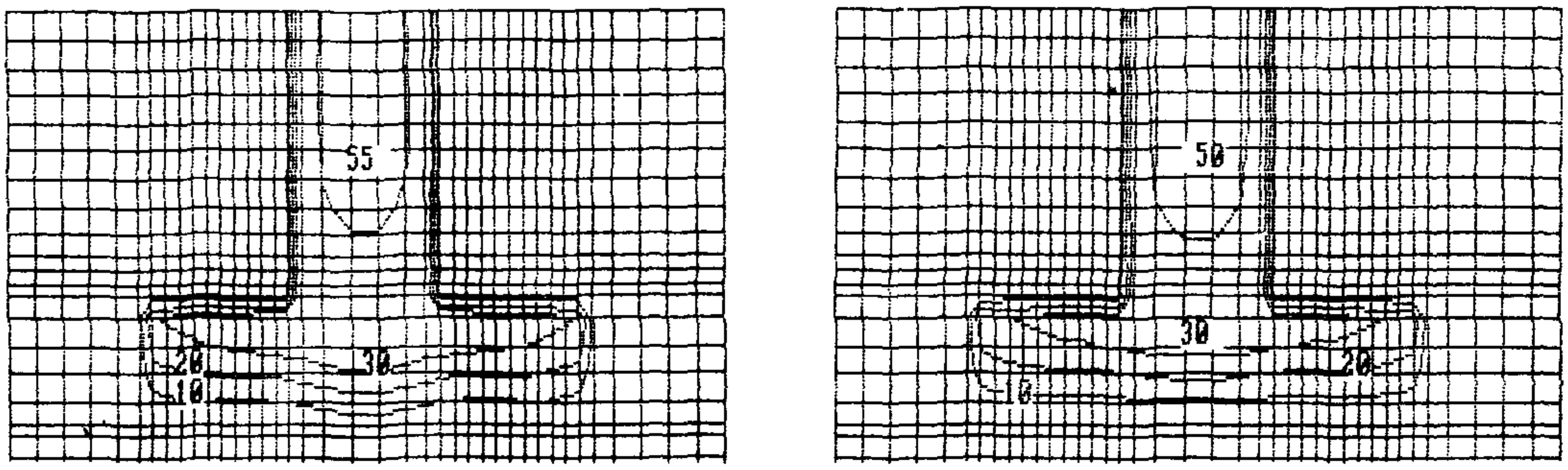
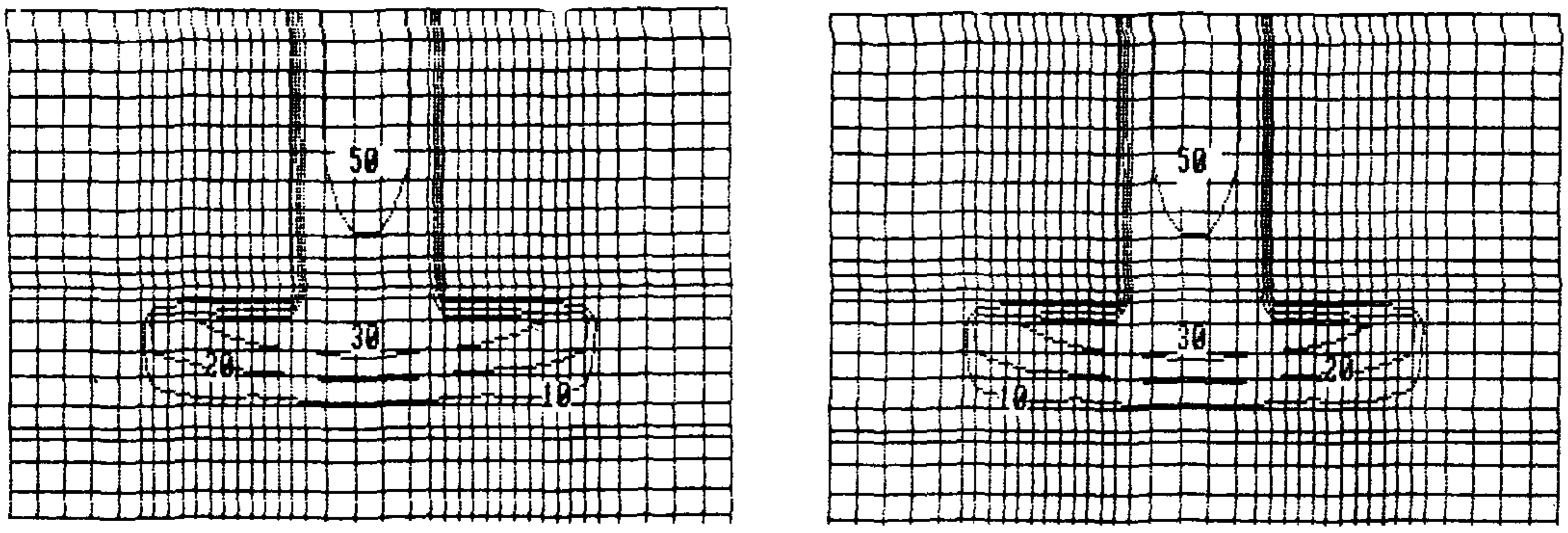
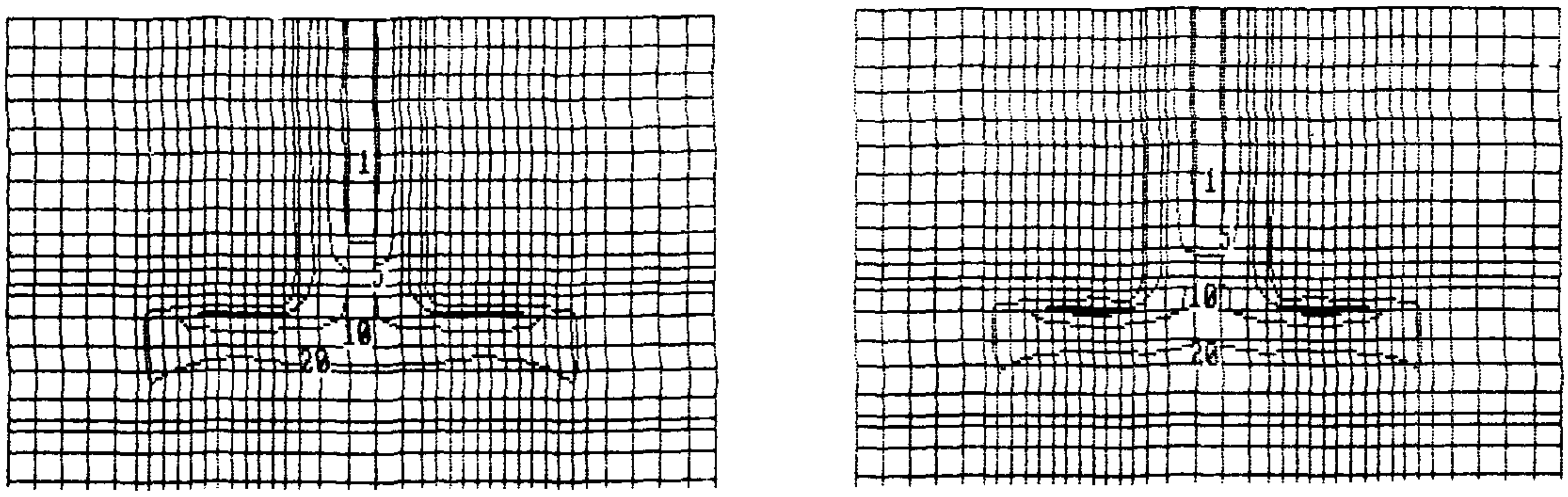


CYCLE 1 CYCLE 3

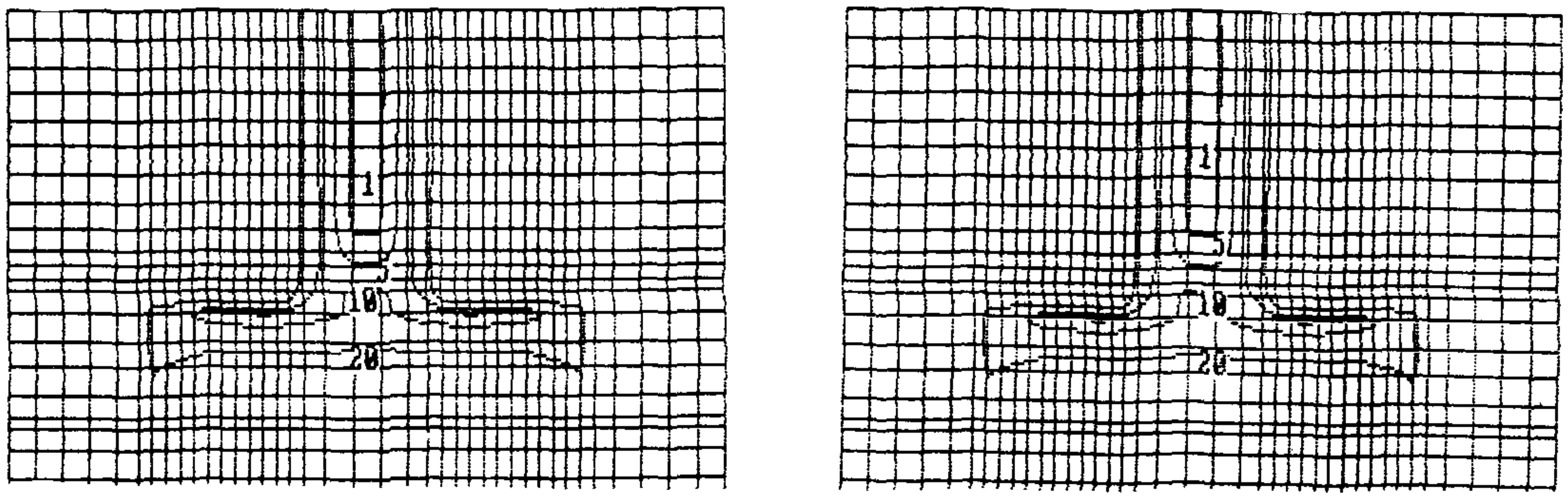


CYCLE 5 CYCLE 6

Fig. 9 Solidification time contour lines for with cooling channels.

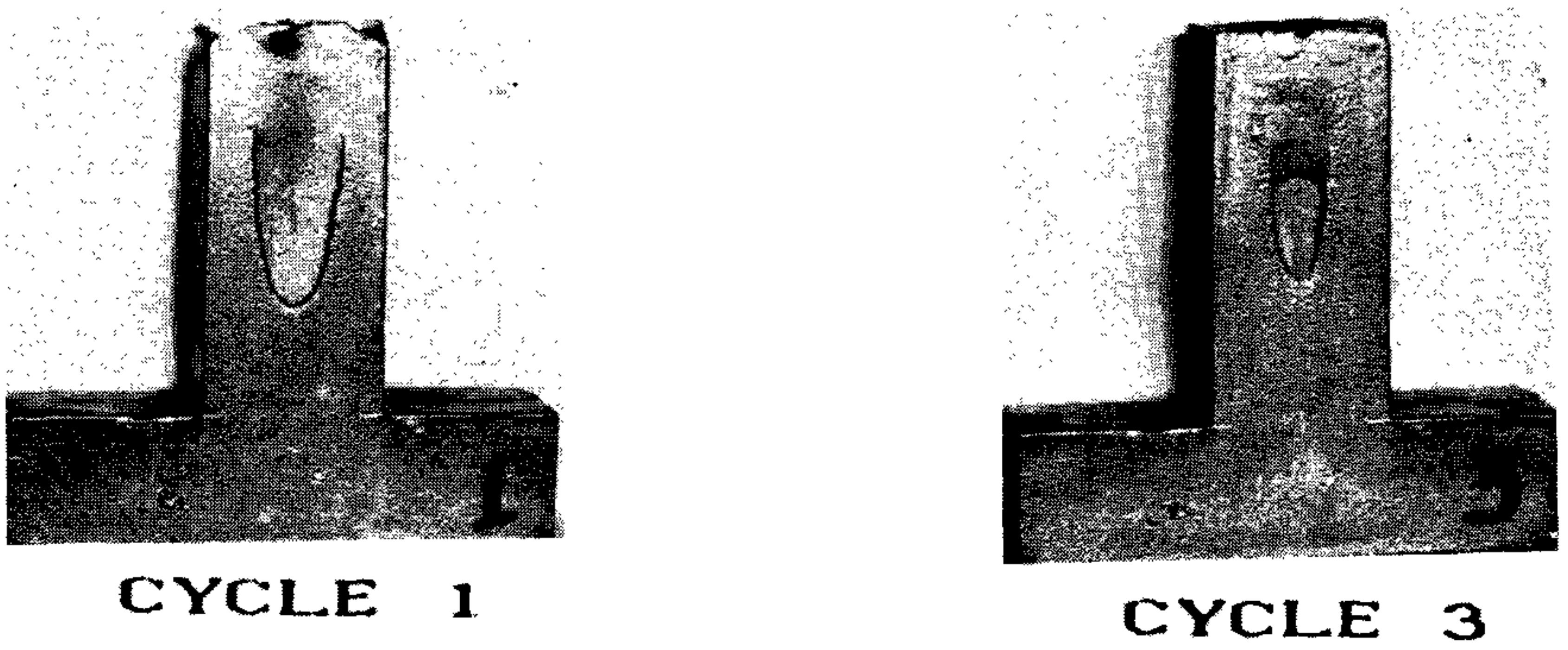


CYCLE 1 CYCLE 3

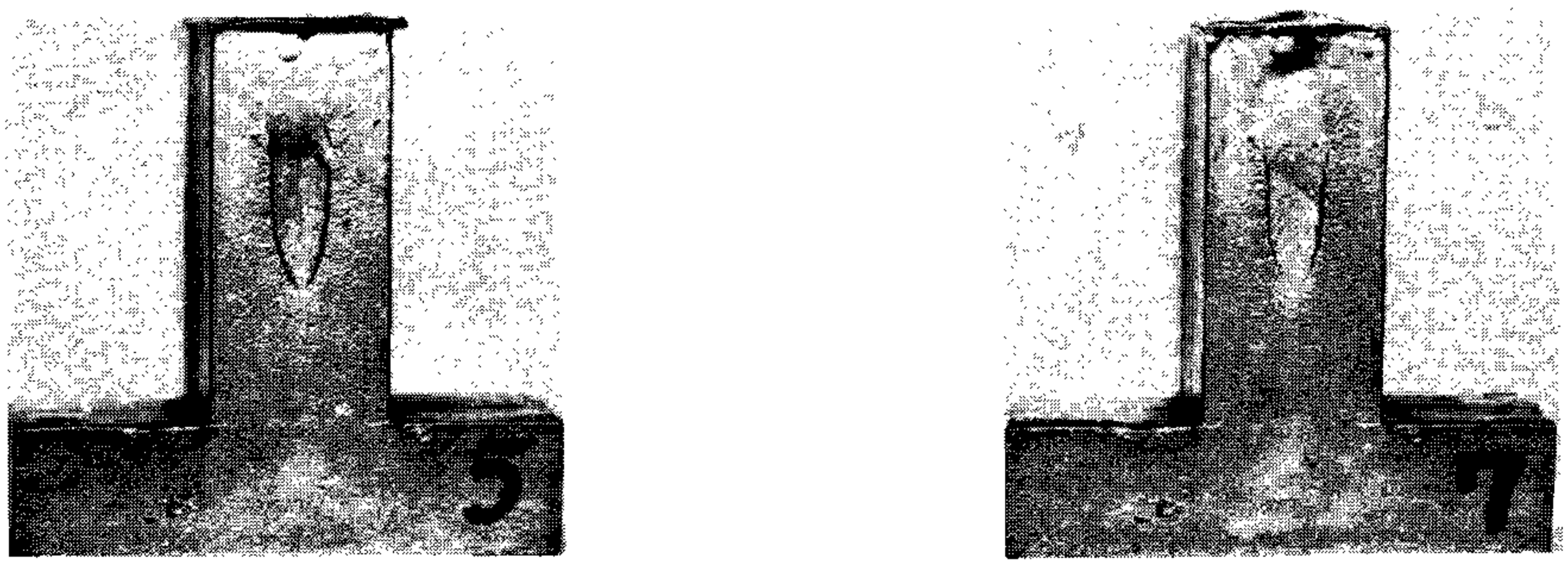


CYCLE 5 CYCLE 6

Fig. 10 Temperature gradient contour lines for with cooling channels

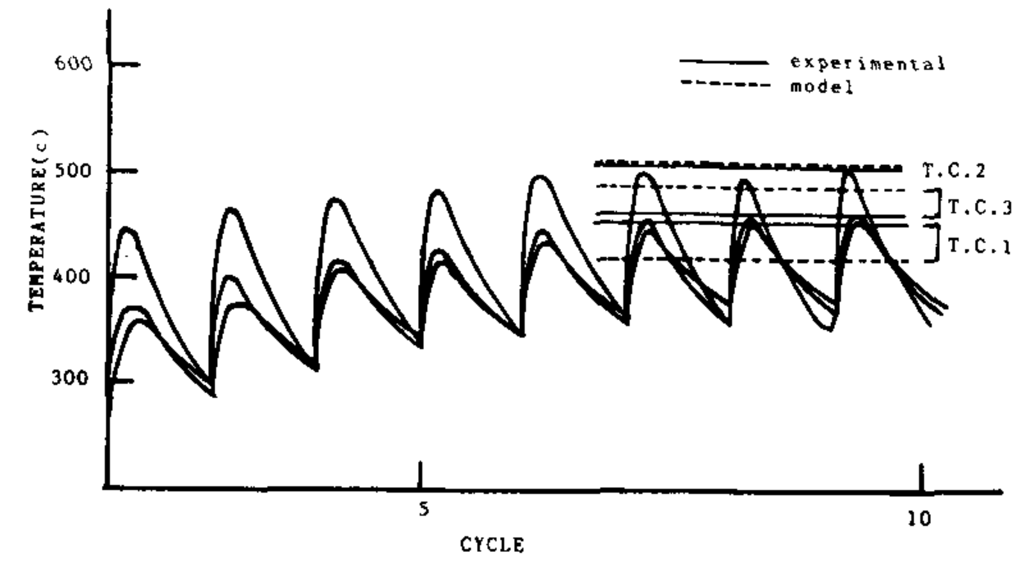


CYCLE 1　　CYCLE 3

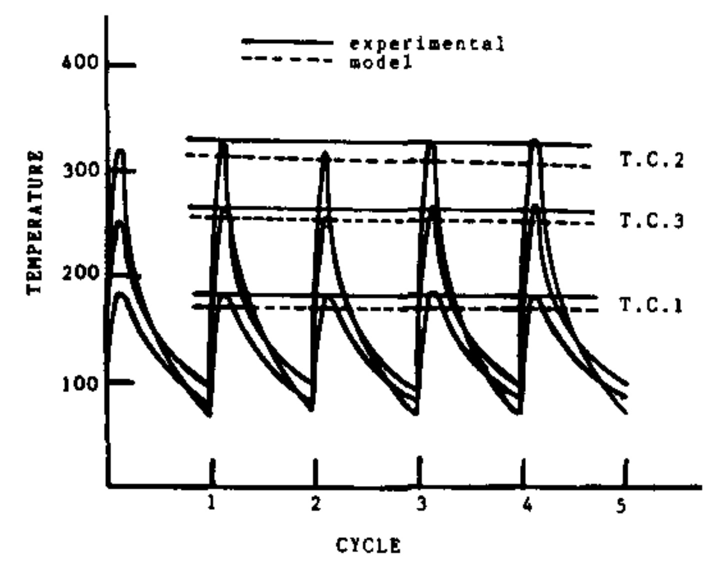


CYCLE 5　　CYCLE 7

Fig. 11 Results of experimental castings for with cooling channels.



(a) without cooling channels



(b) with cooling channels

Fig. 12 Mold temperature profiles during cyclic process of a gravity die casting.

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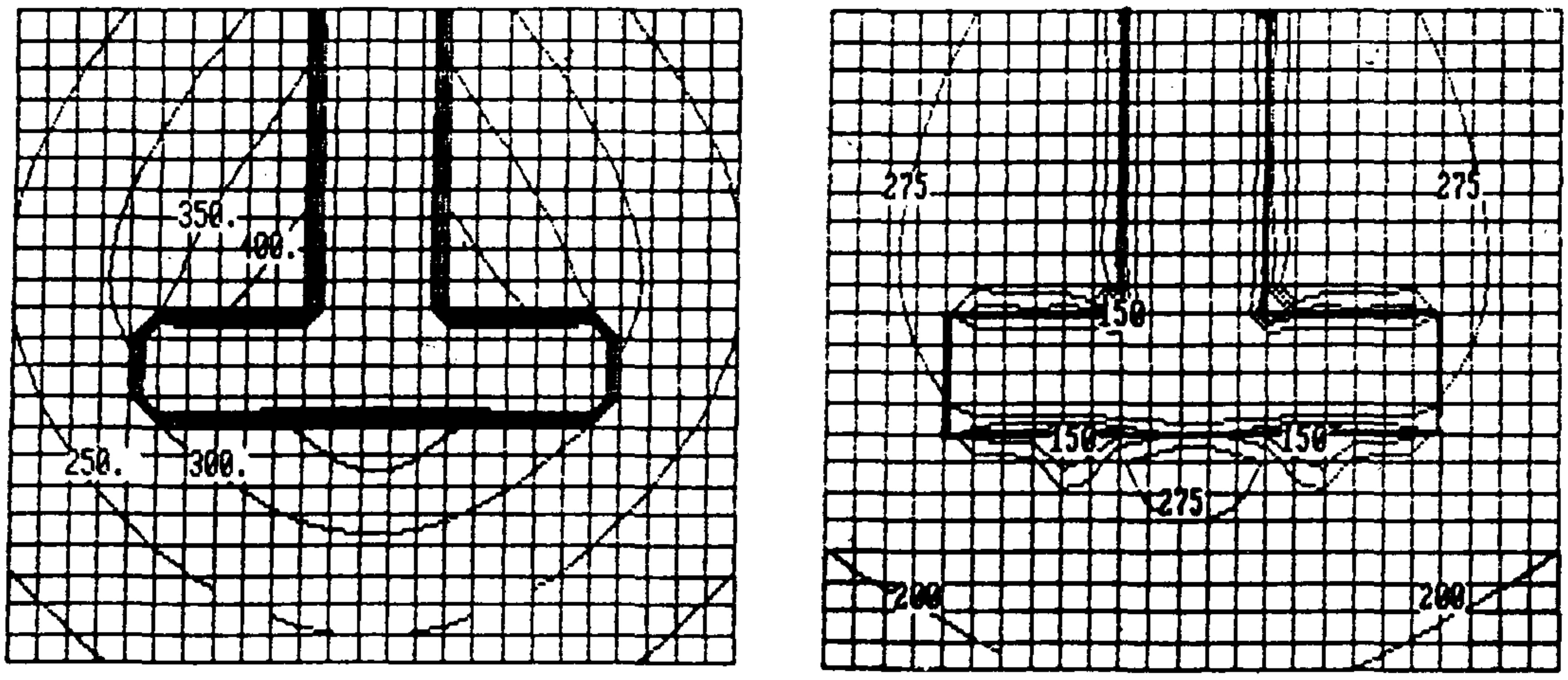

Fig. 13 Calculated temperature distributions of the mold region by the BEM.

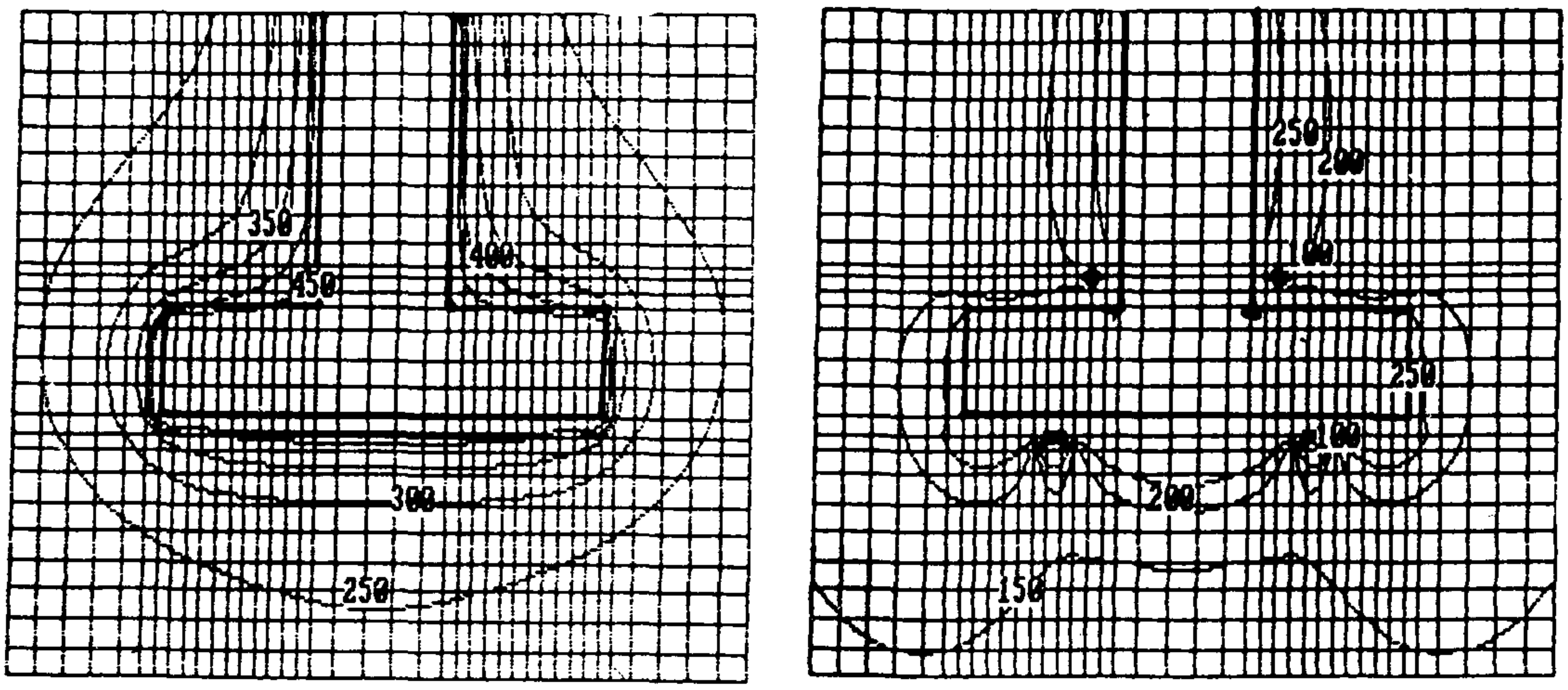

Fig. 14 Calculated temperature distributions of the mold region by the FDM.

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