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ROLE OF THE CONTACT LAYER IN CONTINUOUS CASTING OF THIN METAL RODS

WPŁYW WARSTWY KONTAKTU NA PROCES ODLEWANIA CIĄGŁEGO CIENKICH PRĘTÓW METALOWYCH

An analytical heat transfer model has been development and applied for calculating the shape of the solid thickness profile for continuous casting of thin metal rods. The stationary solidification front relative to the crystallizer was received from superposition of the motions of the liquid metal flow in the axial direction and the solidifying metal in the radial direction. The shape of the solidified crust depends on several parameters. The influence of the contact layer between the frozen crust and the internal surface of a crystallizer on the solidification process is also studied. The results are presented as an analytical model and are graphically shown for different selected parameters.

Keywords: continuous casting, solidification stationary front, contact layer

W pracy bada się analitycznie i oblicza się kształty frontów krzepnięcia przy odlewaniu ciągłym cienkich metalowych prętów. Określono stacjonarny front krzepnięcia względem krystalizatora przez superpozycję dwóch ruchów: przepływu ciekłego metalu w kierunku pionowym i rozprzestrzenianie się frontu krzepnięcia w kierunku promieniowym. Szczególną uwagę zwrócono na opór cieplny warstwy kontaktu między metalem i powierzchnią wewnętrzną krystalizatora. Wykazano zależność kształtu frontu krzepnięcia od parametrów termodynamicznych i przepływowych metalu. Wyniki badań wybranych metali przedstawiono w formie graficznej.

Nomenclature

λ	–	thermal conductivity, $[W/(m \cdot K)]$
c	–	specific heat, $[J/(kg \cdot K)]$
ρ	–	density, $[kg/m^3]$
L	–	latent heat, $[J/kg]$
u	–	mean velocity of the liquid metal flow, $[m/s]$
H	–	length of crystallizer, $[m]$
R	–	radius of crystallizer, $[m]$
T_F	–	liquid metal fusing point, $[K]$
T_0	–	temperature of cooling water, $[K]$
α_0	–	heat transfer coefficient between channel wall and cooling water, $[W/(m^2 \cdot K)]$
α	–	heat transfer coefficient between liquid metal and crust, $[W/(m^2 \cdot K)]$
α_{CON}	–	heat transfer coefficient in the contact layer, $[W/(m^2 \cdot K)]$
T_W	–	surface temperature, $[K]$
t	–	time, $[s]$
x	–	coordinate, $[m]$
r	–	local values of the solidification front, $[m]$

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1. Introduction

The continuous casting of metals is a very important and well-known technology. It is described in detail in both the scientific and the professional literature [1-7]. These papers present numerical methods for the calculation of a slab produced in a continuous casting process. A special technology is applied for the continuous casting of thin metal rods. In [8] the slow solidification of a cylinder with constant heat flux is analyzed. However, the development of the shape of the solidification front has not been investigated. The shape and development of the solidification front is very important in continuous casting of cylindrical rods, because an appropriate shape of the solidification front in the casting process guarantees its continuity. This is the main subject of this paper.

Thus, the development of a simple theoretical model, which can be used practically in planning the technological process of continuous casting of thin rods is required. Thanks to the high thermal conductivity of the metal these particular casting processes allow using simplifying assumptions leading to an analytical investigation.

Thus, the heat transfer between a liquid metal flow inside a cylindrical channel and the surface of this channel is a very important technical problem of continuous casting. Between the flowing liquid and the surface there is an additional resistance of the flow of heat from the heat source (liquid metal) to the cold surface. The reason of this resistance is the contact layer which arises there.

The role of the contact layer for the flow of heat in continuous casting processes is very important and might dominate over other factors. The analysis of the role of the contact layer in a solidification process was recently studied experimentally and theoretically by Loulou et al. [9-11], by Lipnicki [12], by Lipnicki et al. [13] and by Lipnicki and Weigand [14, 15].

General studies on the impact of the developing solidified layers on the solidification process of the flowing liquid on the cold surface are very important from both the practical and the theoretical point of view. The theory of the development of a solidified layer has been investigated in the past in many papers. In the literature there are a lot of works [16] on this subject. In practice, this problem also occurs in the production of thin metal rod.

Beside other things the impact of the contact layer on continuous casting process for thin metal rods is examined in this paper.

2. Problem formulation and solution

It is assumed that a liquid metal flow with the heat of fusion L, the density ρ, the kinematic viscosity ν and the diffusivity of heat a_L has the mean velocity u and the temperature T_L which is larger than the solidification temperature T_F inside the cylindrical channel (crystallizer, see Fig. 1). A frozen layer with radius r is formed on the cold surface of the channel, which has both the radius R and the length H. The temperature of the cold surface is equal to T_W, which is lower than the fusion temperature T_F of the liquid metal. Thus, the contact layer is established between the flowing liquid metal and the cold surface of the channel. This contact layer (small gap) causes an additional resistance of the heat flow $\lambda/(\alpha_{CON}R)$. Across the contact layer, there is the temperature difference $\left(\bar{T} - T_W\right)$; where $\bar{T}$ is the temperature of the inner surface of the frozen layer (see Fig. 2). Between the channel wall and the cooling water with the temperature T_0 the resistance $\lambda/(\alpha_0 R)$ is present for transferring the heat flux to the water.

In addition, the thickness of the frozen layer $(R - r)$ is also of importance in the problem.

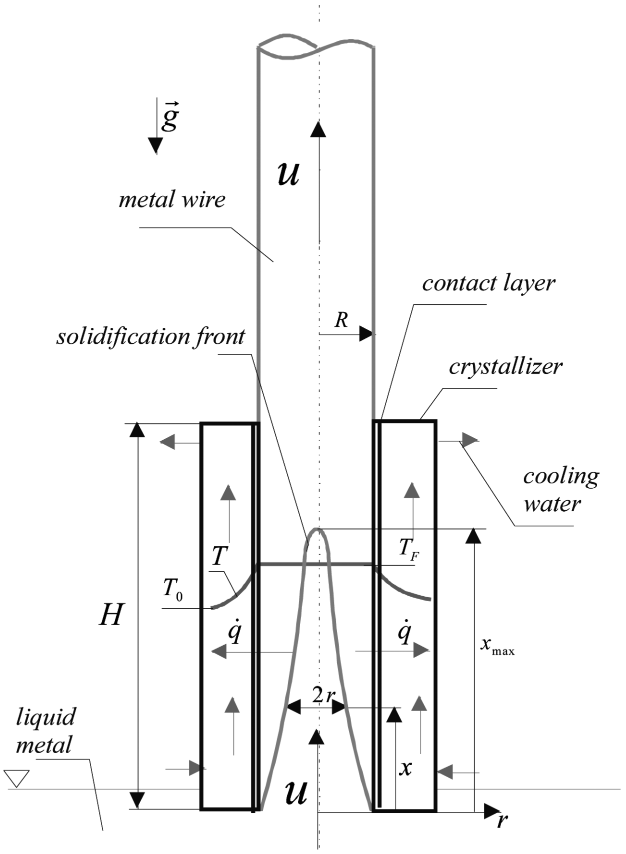

Fig. 1. Sketch of the investigated continuous casting process

During the development of the frozen layer on the cold surface the velocity of the frozen layer thickness is given by$-dr/dt$. The main object of this paper is the description of the thickness of the frozen crust depending on the cooling conditions, which are determined by the properties of both the cold surface and the liquid metal flow.

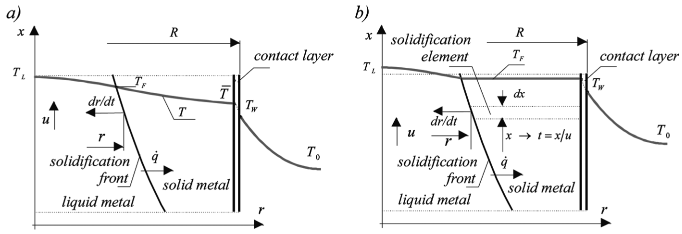

Fig. 2. Simplified models for a solidifying element: *a*) Model-1: Frozen layer with non-perfect conduction; *b*) Model-2: Frozen layer with perfect conduction

The solidification time of an element (see Fig. 2), depends on its position relative to the beginning of the mold determined by the equation

$$t = x/u. \tag{1}$$

The result of the solidification process, the solidified material, is given by the difference between the interface and the center of the channel. Liquid-solid phase-change heat transfer phenomena (solidification) are accompanied by the release of thermal energy. The heat flux per area q released in the interface is transferred through the frozen layer to the crystallizer. We make the simplifying assumption that the solidification front is sharp. We assume that the change of the accumulated heat of the frozen layer is very small. All thermodynamic parameters are assumed to be constant.

2.1. Model-1: Frozen layer with non-perfect conduction ($T_F > \bar{T}$)

The energy balance with equates the latent heat and the heat from the liquid metal flow by convection to the frozen layer can be described as

$$2\pi r\alpha\,(T_L - T_F) - 2\pi\rho Lr\frac{dr}{dt} = 2\pi\lambda\frac{T_F - \bar{T}}{\ln\left(\frac{r}{R}\right)} = \\ 2\pi R\alpha_{CON}(\bar{T} - T_W) = 2\pi R\alpha_0(T_W - T_0) \tag{2}$$

The expression on the left side of equation (2) contains the heat from the liquid metal flow and the heat flux from the solidified metal. The subsequent expressions show the heat flux through the contact layer and the heat flux transferred to the cooling water.

For the outer surface of the contact layer one obtains from equation (2)

$$T_W = \frac{\alpha_{CON}}{\alpha_{CON} + \alpha_0}\bar{T} + \frac{\alpha_0}{\alpha_{CON} + \alpha_0}T_0 \quad \text{and} \tag{3}$$

$$\bar{T} = \frac{1}{1 + R\frac{\alpha_{CON}\alpha_0}{\alpha_{CON}+\alpha_0}\frac{\ln(R/r)}{\lambda}}T_F + \frac{1}{1 + \frac{\lambda}{\ln(R/r)}\frac{\alpha_{CON}+\alpha_0}{R\alpha_{CON}\alpha_0}}T_0 \tag{4}$$

We now introduce the following non dimensionless variables

$$Ste = \frac{c\,(T_F - T_0)}{L}; \quad \tau = SteFo; \quad Fo = \frac{at}{R^2}; \quad \tilde{r} = \frac{r}{R}; \\ \frac{1}{Bi_0} = \frac{\lambda}{\alpha_0 R}; \quad \frac{1}{Bi_{CON}} = \frac{\lambda}{\alpha_{CON}R}; \quad \vartheta = \frac{\Delta T}{T_F - T_0}\frac{\alpha R}{\lambda} \tag{5}$$

which are the Stephan number Ste, a dimensionless time τ, a dimensionless radius $\tilde{r}$, the dimensionless thermal resistance for heat transfer to the coolant Bi_o, the dimensionless thermal resistance of the contact layer, Bi_{CON} and the parameter overheating ϑ.

After substituting the temperature T_w and $\bar{T}$ given by equation (3) and (4) into equation (2) the following equation is obtained for the time depending radius r, describing the solid/liquid interface position from equation (2)

$$\vartheta\tilde{r} - \tilde{r}\frac{d\tilde{r}}{d\tau} = \frac{1}{\beta - \ln\tilde{r}}, \tag{6}$$

where

$$\beta = \frac{1}{Bi_{CON}} + \frac{1}{Bi_O}$$

This equation can be integrated after separating of variables in order to give the solidification time

$$\tau = \int_1^{\tilde{r}} \frac{\tilde{r}\,(\beta - \ln\tilde{r})}{\vartheta\tilde{r}\,(\beta - \ln\tilde{r}) - 1}d\tilde{r}, \tag{7}$$

the above equation fulfills the initial condition $\tau = 0, \tilde{r} = 1$.

The solidification time depends on the position of the liquid metal flow relative to the inlet of the crystallizer (see Figures 2, 3). At the inlet of the crystallizer (x =0), the solidification time is equal to zero ($t = 0$) and increases with the distance x according to equation (1). However, the solidification front is stationary relative to the crystallizer, because this situation results from the superposition of both motions: Liquid metal flow in the axial direction x with the mean velocity u and the solidifying metal in the radial direction. The solidification time is defined by equation (1).

The above analysis shows that the stationary interface can be expressed by the following equation. From equations (1) and (7) it follows

$$\tilde{x} = \frac{Re\,\Pr\,\tilde{a}}{Ste}\int_1^{\tilde{r}} \frac{\tilde{r}\,(\beta - \ln\tilde{r})}{\vartheta\tilde{r}\,(\beta - \ln\tilde{r}) - 1}d\tilde{r} \tag{8}$$

In this equation, the dimensionless quantities are defined accordingly to

$$\tilde{x} = \frac{x}{R}, \quad Re = \frac{uR}{\nu}, \quad \Pr = \frac{\nu}{a_L}, \tilde{a} = \frac{a_L}{a}. \tag{9}$$

If the liquid metal is not overheated, $\vartheta = 0$, equation (6) reduces to

$$-\tilde{r}\,(\beta - \ln\tilde{r})\frac{d\tilde{r}}{d\tau} = 1. \tag{10}$$

The solution of the above equation with the initial condition $\tau = 0, \tilde{r} = 1$ can be obtained easy

$$\tau = \frac{\tilde{r}^2}{2}\ln\tilde{r} + \frac{2\beta + 1}{4}\left(1 - \tilde{r}^2\right) \text{ and} \\ \tilde{x} = \frac{Re\,\Pr\,\tilde{a}}{Ste}\left[\frac{\tilde{r}^2}{2}\ln\tilde{r} + \frac{2\beta + 1}{4}\left(1 - \tilde{r}^2\right)\right] \tag{11}$$

2.2. Model-2: Frozen layer with perfect conduction ($T_F = \bar{T}$)

Assuming the frozen layer with perfect conduction, so that $\bar{T} = T_F$, equation (2) can be simplified to give

$$2\pi r\alpha\,(T_L - T_F) - 2\pi\rho Lr\frac{dr}{dt} = 2\pi R\alpha_{CON}\cdot(T_F - T_W) = \\ = 2\pi R\alpha_0\,(T_W - T_0) \tag{12}$$

For the outer surface of the contact layer one obtains from equation (12)

$$T_W = \frac{\alpha_{CON}}{\alpha_{CON} + \alpha_0}T_F + \frac{\alpha_0}{\alpha_{CON} + \alpha_0}T_0. \tag{13}$$

After substituting the temperature T_w, given by equation (13), into equation (12) the following equation is obtained for the time depending radius r, describing the solid/liquid interface position

$$r\alpha\,(T_L - T_F) - \rho Lr\frac{dr}{dt} = R\frac{\alpha_0\alpha_{CON}}{\alpha_0 + \alpha_{CON}}\,(T_F - T_0)\,. \tag{14}$$

Introducing the dimensionless variables from equation (6), equation (14) can be written as follows

$$\beta\vartheta\tilde{r} - \beta\tilde{r}\frac{d\tilde{r}}{d\tau} = 1. \tag{15}$$

By using the initial condition that for $\tau = 0, \tilde{r} = 1$, the solidification time and the position of the solidified crust can be obtained as

$$\begin{aligned} \tau &= \frac{1}{\vartheta^2\beta}\left[\ln\frac{1-\beta\vartheta\tilde{r}}{1-\beta\vartheta} - \beta\vartheta\left(1-\tilde{r}\right)\right] \text{ and} \\ \tilde{x} &= \frac{Re\,\Pr\,\tilde{a}}{Ste}\frac{1}{\vartheta^2\beta}\left\{\ln\left[\frac{1-\beta\vartheta\tilde{r}}{1-\beta\vartheta}\right] - \beta\vartheta\left(1-\tilde{r}\right)\right\}. \end{aligned} \tag{16}$$

In this equation, the dimensionless quantities are defined accordingly to (5) and (9). As is can be seen by using the rule of L'Hospital equations (16) reduces to equations (17) in the limit when ϑ tends to zero

$$\tau = \frac{1}{2}\beta\left(1-\tilde{r}^2\right) \text{ and } \tilde{x} = \frac{Re\,\Pr\,\tilde{a}}{2Ste}\beta\left(1-\tilde{r}^2\right). \tag{17}$$

3. Results and discussion

The shapes of the solidified crusts for different external conditions are given in Figures 3, 4, 5. In order to show the quantitative impact of the thermodynamic parameters on the solidification process the corresponding graphs are prepared.

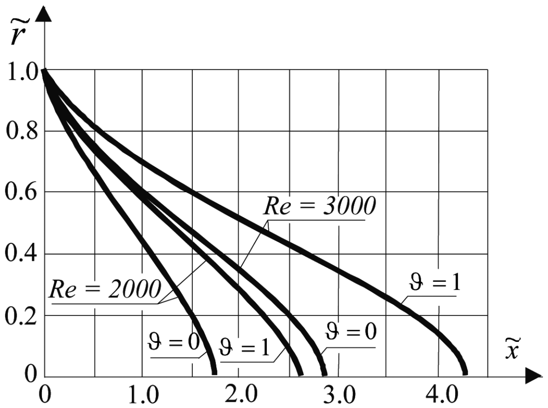

Fig. 3. Solidification front for the liquid metals for $Pr = 0.01$, $Ste = 4$, $\beta = 0.2$, $\tilde{a} = 1.0$

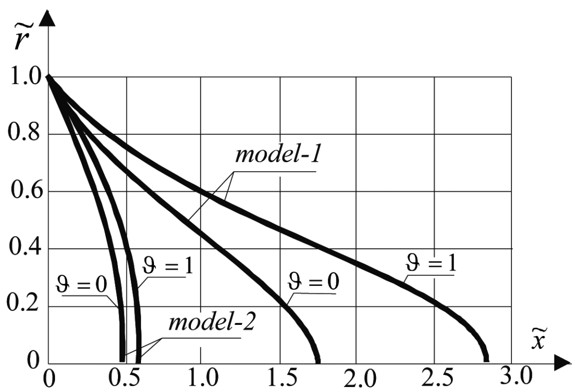

Fig. 4. Comparison of the two solidification models for $Pr = 0.01$, $\beta = 0.2$, $Re=2000$, $Ste = 4$, $\tilde{a} = 1.0$

Figures 3-5 show shapes of the solidification front for different Reynolds numbers and given values of Pr, Ste and different overheat parameters ϑ and different Biot numbers β. As it can easily be seen, the shape and size of the solidification front depend on the resistance of the contact layer $\lambda/(\alpha_{CON}R)$, the parameter ϑ, the Prandtl number Pr and the Reynolds number Re. From the obtained solution it can be seen that the size of the solidification front grows for increasing values of the Reynolds number, the Prandtl number, the resistance of the contact layer and the parameter ϑ.

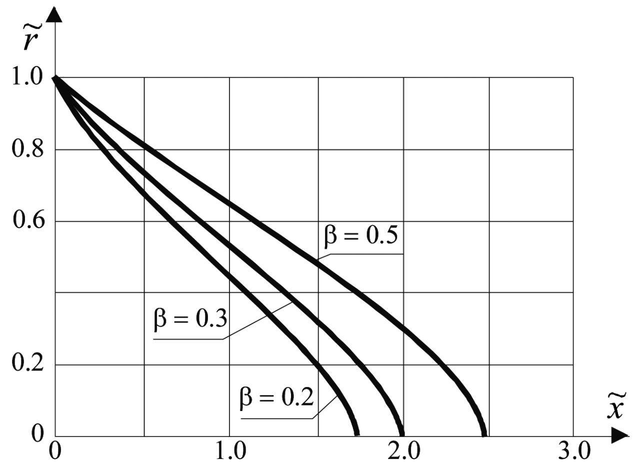

Fig. 5. Solidification front for different values of the parameter β for not overheated liquid metals ($Pr = 0.01$, $Re=2000$, $Ste = 4$, $\tilde{a} = 1.0$)

Figure 4 shows that there is a substantial difference between the results of model-1 and model-2. The simplification of neglecting the resistance of the frozen layer is thus not justified and will lead to wrong physical results.

Figure 5 shows that the role of the contact layer between the metal and the surface of the cooling channel (parameter β) is very important and might dominate in the continuous casting of a thin metal rod.

As can be seen the maximum length of the liquid metal flow corresponds to the radius $\tilde{r} = 0$ and is equal to

$$\tilde{x}_{\max} = \frac{Re\,\Pr\,\tilde{a}}{Ste}\int_1^0 \frac{\tilde{r}\left(\beta - \ln\tilde{r}\right)}{\vartheta\tilde{r}\left(\beta - \ln\tilde{r}\right) - 1}d\tilde{r}. \tag{18}$$

The elevation of the interface should not exceed the height of the mold. This may result in an interruption of the continuous casting process. In addition, the maximum length should satisfy the additional condition

$$\tilde{x}_{\max}R\rho g < p_b, \tag{19}$$

which represents the supply of liquid metal to the mold and guarantees the continuity of the stream.

TABLE 1

Different properties of the metals under investigation. The values are taken from literature [17-20]

metal	T_F K	L kJ/kg	λ W /(m ·K)		ρ kg/ m^3		a m^2 / s $\cdot 10^{-5}$		ν m^2 / s $\cdot 10^{-6}$	Pr
			liquid	solid	liquid	solid	liquid	solid	liquid	liquid
copper	1356	204	250	330	8300	8920	5.54	8.81	0.476	0.0086
aluminium	933	390	104	240	2380	2700	3.39	8.89	0.483	0.0142
tin	506	59	33	66.8	6978	7298	2.01	4.13	0.267	0.0120
silver	1233	111	357	382	9320	10490	12.4	15.8	0.425	0.0034

Table 1 gives the thermodynamic properties of the four metals: copper – Cu, aluminium – Al, silver – Ag and tin – Sn. The values are taken from different references in literature [17-20].

Figures 6-7 show shapes of the solidification fronts of the liquid metals for similar external conditions, that are, both at the same flow rates of the liquid metal and the same cooling conditions for comparison. It can be seen that the liquid silver and the liquid copper solidify fastest.

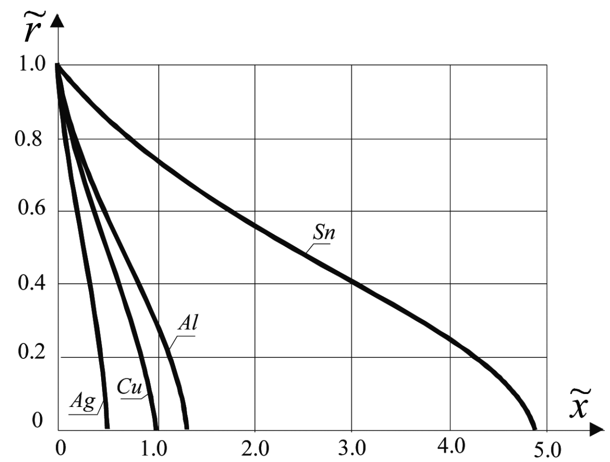

Fig. 6. Solidification front for not overheated liquid metals for u = *0.05m/s*,R = *0.01 m*, β = 0.2, T_0 =*293K*

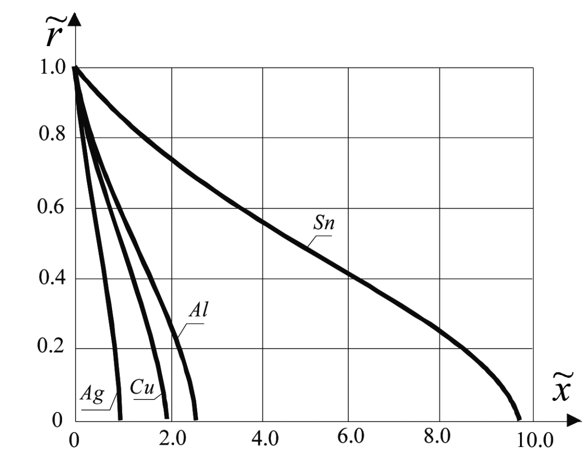

Fig. 7. Solidification front for not overheated liquid metals for u = *0.1m/s*,R = *0.01 m*, β = 0.2, T_0 =*293K*

Aluminium and tin are freezing slowly, so the solidification fronts are more elongated. Knowledge of the shape of the solidification front, especially the maximum height of the solidification front x_{max}, is needed for determining the technological parameters of the continuous process. The special attention should be paid on the property of metals because of differences given in the literature.

4. Conclusions

The paper focuses on the process of continuous casting of a thin metal rod. The solidification of pure liquid metal in an internal crystallizer flow is investigated and a simplified analytical model is presented. The role of the contact layer between the metal and the surface of the cooling channel is very important and might dominate in the continuous casting of a thin metal rod. A simple analytical model is used to predict the freezing fronts for different metal flows. It is seen that these fronts might differ drastically, depending on the type of metal used. Also the influence of the boundary conditions on the development of the frozen crust can nicely been studied by using the simple model presented here.

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