



Development of the contact layer and its role in the phase change process



B. Weigand^a, Z. Lipnicki^{b,*}

^a Institut für Thermodynamik der Luft- und Raumfahrt, Universität Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany

^b Institute of Environmental Engineering, University of Zielona Góra, 65-516 Zielona Góra, Poland

ARTICLE INFO

Article history:

Received 26 May 2015

Received in revised form 28 October 2015

Accepted 28 October 2015

Keywords:

Phase change

Solid layer

Contact layer

Solidification

ABSTRACT

The paper presents a simplified theoretical analysis of liquid solidification on cold flat and cylindrical walls with special emphasis on the role of the contact layer that forms on them. The theory is based on analytical calculations adapted from the kinetic theory of gases. The results show the dependence of the thickness of the contact layer on the thickness of the solidified layer. In addition, the influence of the contact layer on the solidification process has been shown. The development of the thickness of the solidified layer and the influence of the contact layer has been determined for selected liquid and solidification parameters.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

In heat transfer processes the contact layer, located at the interface of objects between which heat is transferred, is of importance. The contact layer plays a particularly important role during phase change processes in different materials. In this case, the contact layer is formed between the cold wall and the solidifying liquid. Problems of heat resistance in contact layers during phase change processes have been analysed by several researchers [1–13]. On basis of the existing analysis of the problem, it is possible to conclude that our knowledge of this phenomenon is still very limited.

The interesting and often quoted experimental analysis on the heat resistance of the contact layer by Loulou et al. [1–3] and Wang and Matthys [4] are regarded as a basis of research, which however, might now be considered to be quite out of date. Research methods used by the above mentioned authors are based on temperature measurements by means of thermocouples traversing through the contact layer. This provides a basis for determining of the heat resistance of the layer. The above mentioned research can therefore be regarded as a starting point for further research both theoretical and experimental.

Theoretical solutions and experimental studies on the thermal contact resistance (TCR) by Artyukhin et al. are given in [6–8]. In [6] the contact resistance was determined theoretically, using an inverse mathematical model for two infinite layers. In [7] an algorithm for determining the thermal contact resistance between a

fuel and a fuel-element shell of a nuclear reactor has been presented. In [8] experiments were shown which confirmed the theoretical model. In these works, there was the release of volumetric energy in the fuel element and the temperature of the process was high.

Publications by the groups of Lipnicki and Weigand [9–14] present theoretical and experimental research on the thermal resistance of the contact layer and its development. The presented mathematical, experimental and analytical methods are based on measurement during the solidification front, which provide a basis for determination of the heat resistance of the contact layer.

The problem of the resistance of the contact layer is still an open question, which is of importance. Nevertheless, it is neglected by a large number of researchers who deal with solidification problems. They are obviously aware of its existence and even adopt a value of heat resistance for the contact layer, however, no detailed research is made which might be related to the large number of influencing parameters for the contact layer.

If we solve the problem of solidification in the area under consideration but ignore the influence of the contact layer, this can lead to erroneous results. Thus, the knowledge of the contact layer influences the correctness of the limit, boundary and initial conditions while constructing and solving behaviour equations.

The contact layer is a place of discontinuity of thermodynamic parameters describing the phenomenon and it occupies a very small space. For this reason its theoretical description with modern calculation techniques (numerical methods) is difficult. The small size of the contact layer requires special theoretical models based

* Corresponding author.

Nomenclature

a	heat diffusivity [m^2/s]
B	cooling parameter $=k_s(T_F - T_W)/(k_L(T_L - T_F))$ [-]
c_p	specific heat at constant pressure [$\text{J}/(\text{kgK})$]
Fo	Fourier number $=at/H^2$ or $=at/R^2$ [-]
k	heat conductivity [$\text{W}/(\text{mK})$]
H	depth of the channel [m]
R	radius of the cylinder [m]
h	heat transfer coefficient $=\dot{q}/(T_L - T_F)$ [$\text{W}/(\text{m}^2\text{K})$]
L	latent heat [J/kg]
Nu	Nusselt number based on R or H $=hR/k_L$ or $=hH/k_L$ [-]

\dot{q}	heat flux [W/m^2]
Ste	Stefan number $=c_p(T_L - T_F)/L$ [-]
t	time [s]
T	temperature [K]
T_F	liquid fusion temperature [K]
T_L	temperature of the liquid [K]
ρ	density [kg/m^3]
δ	frozen layer thickness [m]
δ_C	contact layer thickness [m]

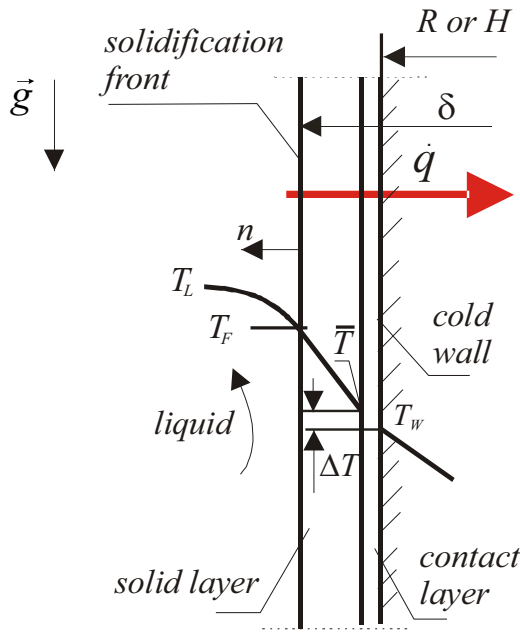


Fig. 1. Liquid solidification on a cold wall.

on the physics of gases in narrow gaps as well as a return to analytical descriptions proven in such cases. Simplicity is not a disadvantage when there is a problem to solve. On the contrary, it is an advantage as long as the nature of the problem is correctly and adequately described. In this paper the problem of the heat resistance of the contact layer is continued and expanded.

2. Solidification and the contact layer

Between a cold wall and a solidified liquid, a gap forms as a consequence of lack of direct contact between these objects. The existence of the gap causes an additional heat resistance. The thickness of the contact layer, its rate of change and the heat transfer resistance during the solidification process all depend on the shape of the solidifying material and the development of the solidification front. In order to fully examine the contact layer, it is necessary to examine each case of solidification individually, taking into account the shape of the cold wall and the geometrical shape of the solidifying material. This paper presents an attempt to find a quantitative connection between the width of the gap that forms and the thickness of the solid layer for two different geometrical shapes: a flat and a cylindrical geometry. Another problem is the phenomenon itself that occurs in the gap. It influences the heat

resistance of the layer. The question arises as to how much does the phenomenon in the gap and the width of the gap influence the total heat resistance?

The liquid solidification process takes place on a cold wall (Fig. 1) if the wall surface temperature T_W is lower than the liquid solidification temperature T_F . Between the surface of the cold wall and the surface of the solid layer with the temperature \bar{T} there appears a thin gap called the contact layer. In the contact layer, temperature changes $\Delta T = \bar{T} - T_W$.

The solidification front moves towards the liquid with the velocity $d\delta/dt$. The heat balance on the solidification front surface of the solid layer with the thickness δ is described by the interface energy equation

$$-k_L \frac{\partial T_L}{\partial n} \Big|_{n=\delta} + k_S \frac{\partial T_S}{\partial n} \Big|_{n=\delta} = \rho_s L \frac{d\delta}{dt} \Big|_{n=\delta} = T_L \Big|_{n=\delta} = T_F, \quad (1)$$

where T_L and T_S denote respectively the liquid temperature and the solid layer temperature, k_L and k_S the liquid heat conductivity and the solid layer heat conductivity, ρ_s is the solid layer density and L denotes the latent heat of solidification.

Free convection might occur in the liquid between the solidification front surface and the cooled wall. Thus, on the interface, the heat flux from the liquid to the solid layer can be described with the equation [9–13].

$$-k_L \frac{\partial T_L}{\partial n} \Big|_{n=\delta} = h(T_L - T_F), \quad (2)$$

where h denotes the heat transfer coefficient between the solidification front and the liquid with the average temperature T_L , which, at a distance from the wall, is assumed to be constant. In the solid layer with the variable thickness δ heat is transferred by conduction.

The balance of heat fluxes on the interphase according to Eq. (1) can be described by Eqs. (2) and (3) as

$$k_S \frac{\partial T_S}{\partial n} \Big|_{n=\delta} = \rho_s L \frac{d\delta}{dt} + h(T_L - T_F). \quad (3)$$

The main cause of the formation of the gap near the cold wall is a change of density of the solid layer near the wall and a drop in temperature (a phenomenon known as casting contraction [17]). The dependence of density on temperature is presented in Table 1 as an example [18].

Table 1
Density and heat conductivity for ice [18].

Temperature (K)	Density (kg/m^3)	Thermal conductivity ($\text{W}/(\text{mK})$)
273.15	917	2.210
253.15	920	2.442
223.15	924	2.780
173.15	928	3.489

Download English Version:

<https://daneshyari.com/en/article/7056347>

Download Persian Version:

<https://daneshyari.com/article/7056347>

[Daneshyari.com](https://daneshyari.com)