

Determination of Thermal Contact Conductance of an Injection Mold Assembly for the Prediction of Mold Surface Temperature

Ki-Yeon Lee¹, Kyeong-Min Kim¹, and Keun Park^{2,#}

¹ Graduate School of NID Fusion Technology, Seoul National University of Science and Technology, Seoul, South Korea, 139-743

² Department of Mechanical System Design Engineering, Seoul National University of Science and Technology, Seoul, South Korea, 139-743

Corresponding Author / E-mail: kpark@seoultech.ac.kr, TEL: +82-2-970-6358, FAX: +82-2-974-8270

(Manuscript received: Sep, 10, 2012 / Revised: Nov, 23, 2012 / Accepted: Nov, 27, 2012)

Injection molds are fabricated by assembling a number of plates in which mold core and cavity components are inserted. The assembled structure causes a number of contact interfaces between each component where the heat transfer is affected by the thermal contact resistance. However, the mold assembly has been treated as a one body in numerical analyses of injection molding, which has a limitation in predicting the mold temperature distribution during the molding cycle. In this study, a numerical approach that considers the thermal contact effect is proposed to predict the heat transfer characteristics of an injection mold assembly. To find the thermal contact conductance between the mold core and plate, a number of finite element (FE) simulations were performed with the design of experiment (DOE) and statistical analysis. Thus, the heat transfer analyses using the obtained conductance values can provide more reliable results than conventional one-body simulations.

KEYWORDS: Finite element analysis; Heat transfer analysis; Injection mold; Thermal contact conductance; Thermal contact resistance, Design of experiment (DOE)

1. Introduction

Injection molding is one of the most widely used manufacturing processes to produce plastic parts in electronics and automobile industries. In the design of the injection molding process, various process parameters including the injection pressure, injection speed, resin temperature, mold temperature, and packing pressure should be investigated in order to improve the quality of the molded parts. From these parameters, the mold temperature is known to be one of most important process parameters that affects the flow characteristics, surface appearance, part deformation, mechanical properties, etc.⁽¹⁾

The mold temperature is usually controlled using cooling channels or heating elements. During the mold filling stage, the mold temperature should be maintained sufficiently high to prevent solidification of the molten polymer. After the filling stage, in contrast, it should be cooled as rapidly as possible in order to reduce the cycle time. Thus, the heat transfer characteristics inside the injection molds should be carefully designed and investigated to improve the part quality and the production time and costs⁽²⁾.

Numerical analyses have been used to predict the temperature distribution of the mold under given cooling or heating conditions. In general, the temperature field of an injection mold is calculated using the finite difference method⁽³⁾ or boundary element method⁽⁴⁾. Recently, 3D finite element (FE) analyses were introduced to solve

the transient heat transfer problem in injection molds, coupled with mold filling simulations⁽⁵⁾. However, these approaches were performed under the assumption that the mold material is a single solid even though a number of components are assembled to construct the injection mold.

It is known that a thermal resistance exists when two thick solid bodies are in contact⁽⁶⁾; therefore, the heat flow through the interface region is affected by these contact surfaces. Thus, the effect of the thermal contact resistance in the interface region should be considered in order to more accurately predict the temperature distribution in injection molds. In the previous studies of the authors, the thermal contact effect was taken into account in numerical analysis using air gap layers which simplify the contact resistance at the interface regions⁽⁷⁾, and further applied to the thermal-fluid coupled analysis of injection molding⁽⁸⁾.

In the present study, the thermal contact effect is investigated by calculating the thermal contact conductance value. The conductance value is initially calculated by theoretical approach. FE simulations considering the thermal contact conductance are then performed to predict the heat transfer characteristics of an injection mold assembly. Statistical analyses with the DOE are followed in order to find the optimal conductance values to minimize the simulation error compared with experimentally-measured temperature results.

2. Theoretical background for thermal contact resistance

When two solid bodies come into contact with each other, a temperature drop is observed at the interface between the two contact surfaces. The thermal contact conductance (h_c) is the property that indicates the thermal conductivity between the two bodies in contact. The thermal contact resistance (R_c), which is inversely proportional to h_c , is defined as the ratio of the temperature drop (ΔT) to the average heat flow across the interface (q).

Figure 1 presents a schematic diagram of the thermal contact in an injection mold assembly in which a mold core (material 2) is inserted into a mold plate (material 1). Because the contact surfaces of these two bodies are not perfectly flat, only a few spots are actually in contact while an air gap exists at most interface regions as shown in the detailed view of Fig. 1. It is known that the actual contact region does not exceed 2% of the entire contact interface⁽⁹⁾.

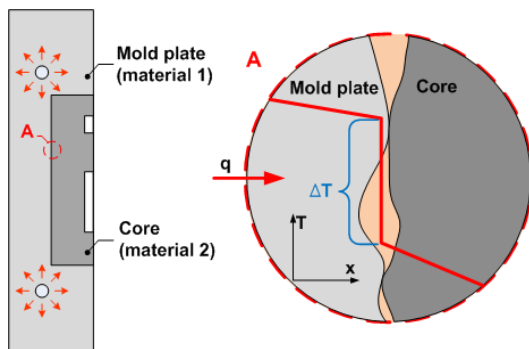


Fig. 1 Schematic diagram of the thermal contact in a injection mold assembly

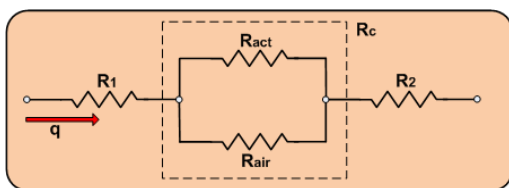


Fig. 2 Thermal-electrical analogy for the contact resistance between two solid bodies

The thermal contact resistance between two solid bodies can be calculated using the thermal-electrical analogy shown in Fig. 2. For the heat transfer from the mold plate (material 1) to the core (material 2), the overall thermal resistance (R_{ovr}) can be calculated using the following equation:

$$R_{ovr} = R_1 + R_c + R_2 = \frac{l_1}{k_1 A_1} + R_c + \frac{l_2}{k_2 A_2} \quad (1)$$

where k , A , and l represent the thermal conductivity, cross-sectional area, and length for each material, respectively. The thermal contact resistance (R_c) is expressed using the following relation:

$$R_c = \frac{R_{act} R_{air}}{R_{act} + R_{air}} \quad (2)$$

where R_{act} and R_{air} denote the thermal contact resistances of the actual contact region and the air gap region, respectively. R_{air} can be expressed using the following relation⁽¹⁰⁾:

$$R_{air} = \frac{\delta_{eff}}{2k_{air}}(1-\varepsilon)^2 \quad (3)$$

where δ_{eff} is the effective height of the micro-roughness and ε is the shape factor of the contact. Thus, the thermal contact resistance for the air region can be calculated from Eq. 3 by measuring the surface roughness on the contact surface.

The contact resistance of the actual contact region (R_{act}) can be calculated using the following equation⁽¹⁰⁾:

$$R_{act} = \frac{1}{2.1 \times 10^4 k_m \eta} \quad (4)$$

where k_m is the thermal conductivity of the material in contact and η is the ratio of the actual contact area. However, this contact ratio cannot be easily determined because it depends on the micro-roughness of the contact interface. In this study, a numerical investigation is performed to determine the thermal contact resistance (conductance) inside the injection mold assembly by combining FE thermal analyses and statistical analyses with the DOE approach.

3. Investigation of the thermal contact effect in the injection mold

3.1 Initial calculation of thermal contact conductance

The injection mold assembly is composed of two components (a mold plate and a core) as shown in Fig. 3. The specifications of these two components are listed in Table 1. Two types of contact interfaces exist in this mold assembly: a bottom contact interface and four side contact interfaces. The side clearances between the mold core and plate were designed to be 100 μ m in order to facilitate the assembly procedure. The assembly clearances can be regarded as the effective height of the micro-roughness (δ_{eff}) for the side interface. The contact conductance through the side interface (h_s) was then calculated to be 239.10 W/m^2-K using the inverse of R_{air} from Eq. (3).

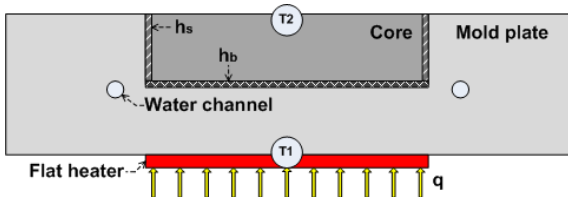


Fig. 3 Configuration of injection mold assembly for the 1D heat transfer experiments

Table 1 Specifications for the injection mold assembly (unit: mm)

Part	Mold plate	Mold core
Material	AISI-1045 steel	AISI-1045 steel
Length	200	100
Width	200	100
Height	50	28

The contact conductance on the bottom contact interface (h_b) is more complicated because it includes the contact resistances in the actual contact region as well as the air gap region. The overall contact conductance was determined through a simplified one-dimensional heat transfer experiment (see Fig. 3). A flat heating element (power: 130 W) was installed on the bottom face of the mold plate and acted as a heat source with a heat flux of 4506.1 W/m^2 . The contact conductance was then calculated using Eq. (5):

$$h_b = \frac{1}{R_c A} = \left[\frac{(T_1 - T_2)}{q} - \left(\frac{l_1}{k_1} + \frac{l_2}{k_2} \right) \right]^{-1} \quad (5)$$

The measured temperature difference (ΔT) was 10.1°C between the top of the mold core (T_2) and the bottom of the plate (T_1). Using Eq. 5, the contact conductance on the bottom interface (h_b) was then calculated to be $808.15 \text{ W/m}^2\text{-K}$. These contact conductance values (h_s and h_b) were then used in the numerical analyses to predict the heat transfer characteristics in the mold assembly, which is discussed in the next section.

3.2 Heat transfer analysis considering thermal contact resistance

In this section, the heat transfer characteristics in the injection mold are investigated through three-dimensional (3D) transient FE analyses. Experiments were also performed by circulating hot water with a temperature of 80°C and flow rate of 13.2 l/min through the two water channels. Figure 4 illustrates the measured thermal image of the mold surface after 300 s, showing the discontinuous temperature distributions across the side contact regions. It can be seen that severe temperature drops were observed at the contact surfaces. The amount of the temperature drop from the mold plate to the mold core (ΔT) was measured to be 21.96°C along the horizontal centerline as denoted in Fig. 4.

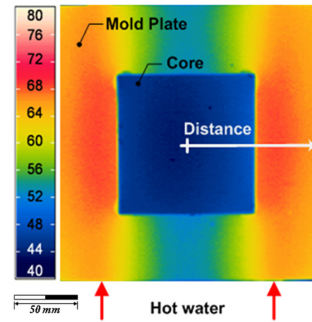


Fig. 4 Measured temperature distributions on the mold surface (unit: $^\circ\text{C}$).

FE analyses were then performed and compared for the aforementioned experiment with and without the thermal contact consideration. ANSYSTM was used in the transient heat transfer analysis. A quarter section of the entire domain was meshed by considering the symmetry condition as shown in Fig. 5. The material density, specific heat, and thermal conductivity for AISI-1045 steel were set to 7850 kg/m^3 , 486 J/kg-K , and 49.8 W/m-K , respectively. The heat convection coefficients were set to $23,234 \text{ W/m}^2\text{-K}$ for the hot water channel and $5.0 \text{ W/m}^2\text{-K}$ for the outer surfaces as boundary conditions⁽⁷⁾. To take into account the effect of thermal contact resistance, thermal contact elements in which contact conductance values were defined were used on the contact surfaces of the mold plate and core, as illustrated in Fig. 5.

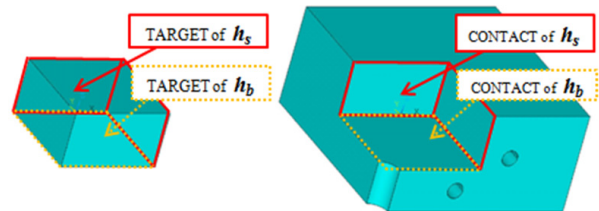


Fig. 5 FE analysis domain including the mold plate, core and thermal contact elements (1/4 section).

FE analysis without consideration of the thermal contact was performed first. The resulting temperature distribution on the mold surface are shown in Fig. 6 (a). It can be seen that this simulation result without consideration of the thermal contact does not show a remarkable temperature drop at the interface, which is significantly different from the experimental result.

The thermal FE analysis was then performed with considering the thermal contact. In this analysis, the thermal contact conductance values were set to the initially calculated values; $808.15 \text{ W/m}^2\text{-K}$ for the bottom interface and $239.10 \text{ W/m}^2\text{-K}$ for the side interfaces. The resulting temperature profile is shown in Fig. 6 (b), representing much more similar trend to the experimental measurement.

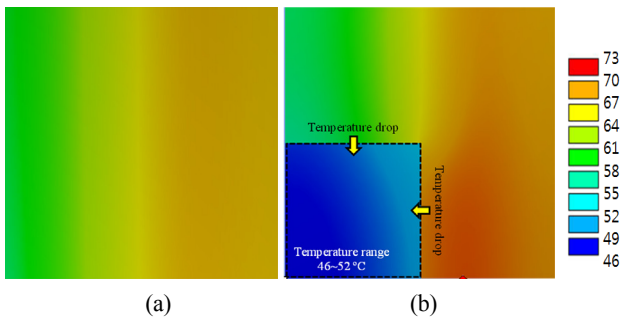


Fig. 6 Temperature distributions on the mold surface obtained from FE analyses (unit: °C): (a) w/o contact consideration and (b) with contact consideration

For a quantitative comparison, temperature profiles on the mold surface from two simulation results are plotted in Fig. 7. The temperature profile obtained from experimental measurement is also added for comparison. It can be seen that the simulation with the contact consideration ensures much more similar trends to the experimental result by predicting the temperature drop at the interface successfully. The amount of the temperature drop was 20.21 °C, which corresponds to an error of 7.97% in comparison with the measured value, 21.96 °C.

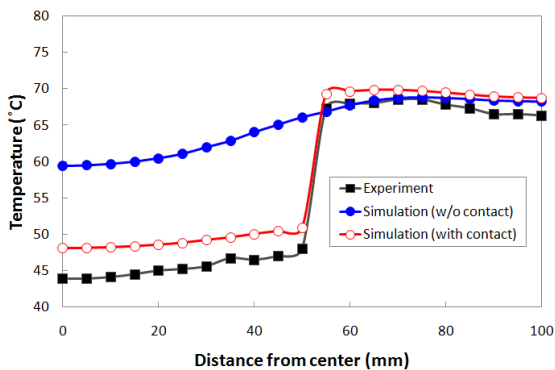


Fig. 7 Comparison of the temperature distributions of the mold surface

3.3 Determination of the thermal contact conductance

Although the consideration of the thermal contact can predict the discontinuous temperature distribution as stated in the previous section, the numerical analysis still had an error of 7.97% in estimating the amount of the temperature drop across the interfaces. This numerical error is caused by the approximations in analytical calculation of the thermal contact conductance. In this study, the DOE and statistical analysis were applied to determine the thermal contact conductance values for the bottom interface and side interfaces of the mold assembly.

Two thermal contact conductance values (h_s and h_b) were selected as design parameters. A full-factorial DOE was scheduled for these two parameters with three levels. Based on the initial calculation of

these conductance values, the three levels were set to 100/200/300 W/m²-K for h_s and 700/800/900 W/m²-K for h_b . The response was the temperature drop on the mold surface (ΔT). Thus, the objective of this DOE is to obtain the optimal conductance values (h_s and h_b) that calculate the temperature drop as close to that of the experiment as possible.

Figure 8 shows the main effect plots for both design parameters. It can be seen that the temperature drops decrease as the contact conductance values increase in both cases, and the effect of h_s is more sensitive than that of h_b . Since these graphs show nearly linear relation, the statistical analysis can be performed using a linear regression model. Figure 9 plots the interactions between h_s and h_b , showing that no significant interaction exists. The regression equation for the temperature drop is then obtained as a function of h_s and h_b :

$$\Delta T = 29.634 - 2.088 \times 10^{-2} h_s - 5.021 \times 10^{-3} h_b \quad (6)$$

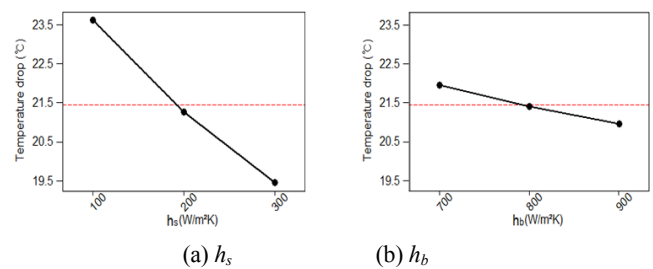


Fig. 8 Main effect plots for two contact conductance values

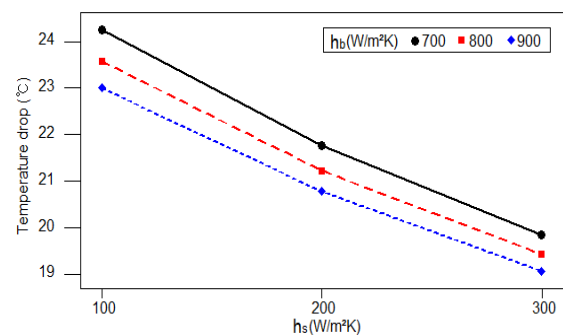


Fig. 9 Interaction plots between two contact conductance values

Knowing that the measured temperature drop was 21.96 °C, h_s and h_b were determined to be 170.6 and 819.0 W/m²-K, respectively, by solving Eq. (6). Thermal FE analyses were then performed using these contact conductance values. The resulting temperature drop calculated through the analyses was 21.76 °C, which corresponds to an error rate of 0.91% compared with the experimental result. Figure 10 compares the amount of temperature drop in the experiment and various simulation results: without considering the thermal contact (Case 1); with analytically determined contact conductance values

(Case 2); and with optimally determined contact conductance values (Case 3). It can be seen that the proposed approach connecting the FE analyses with the DOE (Case 3) can successfully predict the thermal contact conductance values inside the mold assembly.

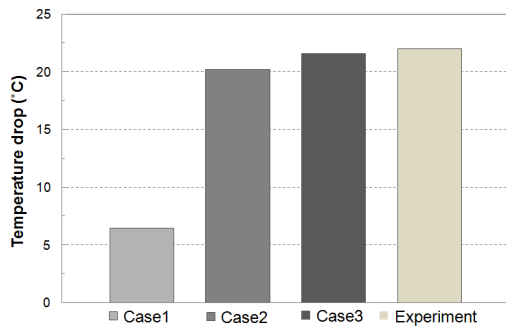


Fig. 10 Comparison of the temperature drop for each case

4. Conclusions

The assembled structure of an injection mold causes the thermal contact at every contact interface where a temperature drop occurs due to its contact resistance. In this study, a numerical approach that considers the thermal contact resistance was developed to predict the heat transfer characteristics of the injection mold assembly. To take into account the effect of thermal contact resistance, thermal contact elements containing contact conductance information were used on the contact surfaces. Thermal FE analyses were then performed to predict the temperature distribution of the mold assembly when hot water was circulated through water channels. It was found that the conventional analysis that does not consider the thermal contact could not predict the temperature drop at the contact interfaces. In contrast, the FE analysis that considers the thermal contact provided more reliable results and can predict the temperature drop to within an acceptable error range.

Furthermore, the effect of the thermal contact conductance was investigated because the amount of temperature drop depended on this value. The first analysis, in which the contact conductance was calculated using the simplified analytic solution, showed an error rate of 7.97% in estimating the amount of the temperature drop. To find the optimal thermal contact conductance to minimize this error, a number of FE simulations were performed with the DOE with a full factorial design. The optimal contact conductance values were then determined through regression analyses. The final FE analysis was then performed by applying the optimized conductance values, and the estimated temperature drop showed only 0.91% error from the experimental result.

Through these results, it can be concluded that the proposed approach connecting the FE analysis with the DOE can predict the thermal contact conductance values inside the mold assembly with high accuracy. Further studies on the mold filling analysis that

considers this thermal contact effect will provide more reliable predictions of the flow characteristics inside the mold by applying more realistic thermal boundary conditions.

ACKNOWLEDGEMENT

This study was financially supported by Seoul National University of Science & Technology.

REFERENCES

- (1) Yao, D., Chen, S. C., and Kim, B., 2008, "Rapid Thermal Cycling of Injection Molds: An Overview on Technical Approaches and Applications," *Adv. Polym. Technol.*, Vol. 27, No. 4, pp. 233~255.
- (2) Park, K., Sohn, D. H., and Cho, K. H., 2010, "Eliminating Weldlines of an Injection Molded Part with the Aid of High-frequency Induction Heating," *J. Mech. Sci. Tech.*, Vol. 24, No. 1, pp. 149~1520.
- (3) Chiang, H. H., Hieber, C. A., and Wang, K. K., 1991, "A Unified Simulation of the Filling and Postfilling Stages in Injection Molding, Part I: Formulation," *Polym. Engng. Sci.*, Vol. 31, No. 2, pp. 116~124.
- (4) Kwon, T. H., 1989, "Mold Cooling System Design using Boundary Element Method," *Trans. ASME J. Engng. Indust.*, Vol. 110, No. 4, pp. 348~394.
- (5) Lin, Y. W., Li, H. M., Chen, S. C., and Shen, C. Y., 2005, "3D Numerical Simulation of Transient Temperature Field for Lens Mold Embedded with Heaters," *Int. Comm. Heat Mass Transf.*, Vol. 32, No. 9, pp. 1221~1230.
- (6) Cooper, M. G., Mikic, B. B., and Yovanovich, M. M., 1969, "Thermal Contact Conductance," *Int. J. Heat Mass Transf.*, Vol. 12, No. 3, pp. 279~300.
- (7) Kim, K. M., Lee, K. Y., Sohn, D. H., and Park, K., 2011, "Investigation into Heat Transfer Characteristics of an Injection Mold by Considering Thermal Contact Resistance," *Trans. Mater. Process.*, Vol. 20, No. 1, pp. 29~35.
- (8) Sohn, D. H., Kim, K. M., and Park, K., 2011, "Thermal-fluid Coupled Analysis for the Injection Molding Process by Considering the Thermal Contact Resistance," *Trans. of the KSME (A)*, Vol. 35, No. 12, pp. 1627~1633.
- (9) Holman, J. P., 1997, *Heat Transfer*, McGraw-Hill, New York, USA.
- (10) Shlykov, Y. P., and Ganin, E. A., 1960, "Thermal Contact Resistance," *Trans. Atom. Energ.*, Vol. 9, No. 6, pp. 496~498.
- (11) Rhee, B. O., Choi, J. H., and Tae, J. S., 2009, "Reduction of Design Variables for Automated Optimization of Injection Molding Cooling Circuits," *Trans. KSMTE*, Vol. 18, No. 4, pp. 417~422.