Springer

Journal of Mechanical Science and Technology 23 (2009) 607~613

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-1123-0

A study on cooling efficiency using 1-d analysis code suitable for cooling system of thermoforming †

Zhen-Zhe Li, Kwang-Su Heo, Dong-Ji Xuan and Seoung-Yun Seol*

Department of Mechanical Engineering, Chonnam National University, 300 Yongbong-dong, Buk-gu, Gwangju 500-757, Korea

(Manuscript Received October 2, 2007; Revised August 18, 2008; Accepted November 24, 2008)

Abstract

Thermoforming is one of the most versatile and economical processes available for polymer products, but cycle time and production cost must be continuously reduced in order to improve the competitive power of products. In this study, water spray cooling was simulated to apply to a cooling system instead of compressed air cooling in order to shorten the cycle time and reduce the cost of compressed air used in the cooling process. At first, cooling time using compressed air was predicted in order to check the state of mass production. In the following step, the ratio of removed energy by air cooling or water spray cooling among the total removed energy was found by using 1-D analysis code of the cooling system under the condition of checking the possibility of conversion from 2-D to 1-D problem. The analysis results using water spray cooling show that cycle time can be reduced because of high cooling efficiency of water spray, and cost of production caused by using compressed air can be reduced by decreasing the amount of the used compressed air. The 1-D analysis code can be widely used in the design of a thermoforming cooling system, and parameters of the thermoforming process can be modified based on the recommended data suitable for a cooling system of thermoforming.

Keywords: Finite difference method; Heat transfer; Thermoforming; Water spray cooling

1. Introduction

Thermoforming is a method of manufacturing plastic parts by preheating a flat sheet of plastic to its forming temperature, then bringing it into contact with a mold whose shape it takes. The sheet is held against the mold surface unit until cooled. The formed part is then trimmed from the sheet. Fig. 1 shows thermoforming process[1, 2].

The focus of this study was on the cooling process, and numerical simulation of cooling system of thermoforming was carried out. ABS sheet is cooled in forming machine before it is transported. In the cooling period, heat is removed by conduction and compressed air. In this study, water spray cooling was used instead of compressed air cooling in order to shorten the cycle time and reduce the cost of compressed air by using developed 1-D analysis code suitable for cooling system of thermoforming. Water spray cooling has been widely applied in the field of surgery, quenching of metal etc.[3-6]. After the preheating process, the temperature of ABS sheet is about 150℃, which means that the cooling period goes through the region of nucleate boiling[7,8]. Therefore, water spray cooling can maximize the cooling efficiency. Fig. 2 shows the boiling curve[9].

2. Prediction of cooling time

The cooling time was predicted in order to check the real condition of compressed air cooling in mass production. The material of the mold was aluminum.

† This paper was recommended for publication in revised form by Associate Editor Dongsik Kim
*Corresponding author. Tel.: +82 62 530 1678, Fax.: +82 62 530 1689
E-mail address: syseol@chonnam.ac.kr

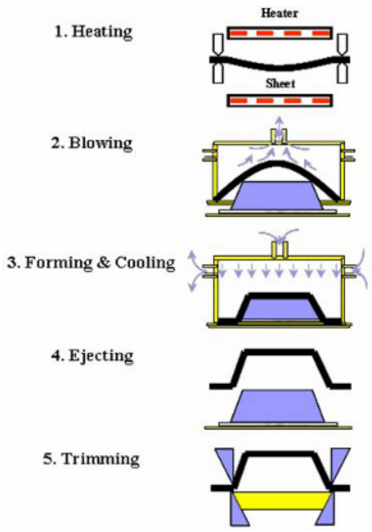

Fig. 1. Thermoforming process.

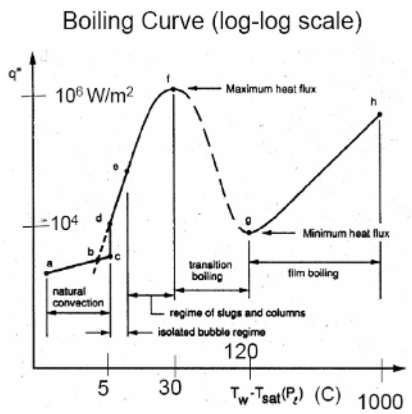

Fig. 2. Boiling curve.

The dimension of the mold was $2 \times 1 \times 0.02$ (m), and the dimension of the ABS sheet was $2 \times 1 \times 0.001$ (m), because the sheet becomes thinner after the process of heating and blowing. Equation 1 could be obtained when the ratio of the energy removed from upper surface (compressed air cooling) among the total removed energy was assumed as 40%.

$$0.4\rho_p Th_p A_p C_p \frac{dT}{dt} = -h_a A_p (T - T_e) \tag{1}$$

Therefore, the cooling time can be calculated from Eq. 2.

$$\frac{0.4\rho_p Th_p C_p}{h_a} \ln\left(\frac{T_i - T_e}{T_f - T_e}\right) = t_{cl} \tag{2}$$

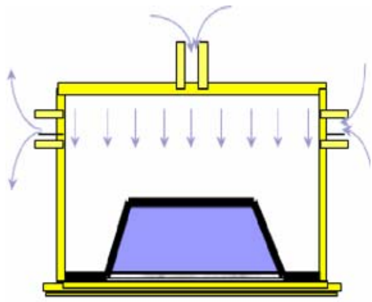

Fig. 3. Mold and sheet in cooling system.

Fig. 4. Analysis model.

The calculated cooling time(t_{cl}) was 11.6s under the condition that the heat transfer coefficient of compressed air cooling(h_a) was assumed as 80W/m^2·K with the initial temperature(T_i) of 150℃ and final temperature(T_f) of 80℃. The calculated cooling time was reasonable compared with the cooling time in mass production(16s). In sum, the compressed air cooling is the limit of reducing the cycle time.

3. Development of 1-D analysis code

3.1 2-D analysis

ABS sheet is cooled by compressed air and mold in mass production as shown in Fig. 3. To check the possibility of changing a 2-D to a 1-D problem, 2-D analysis was performed by using the commercial code - FLUENT. The distance between channels was 125mm, and mold thickness was 30mm. Inner diameter of coolant channel was 4mm, and thickness of channel tube made of stainless steel was 0.6mm. Thickness of sheet made of ABS was assumed as 3mm. Coolant temperature, initial mold temperature and environmental temperature were 75℃, 80℃ and 30℃, respectively. The heat transfer coefficients of coolant cooling of channel, compressed air cooling and water spray cooling were the recommended values of 500W/m^2·K, 100W/m^2·K, 1000W/m^2·K[2,10]. In analysis, contact resistance between sheet and mold was neglected, and symmetry condition was used to reduce the computational effort as shown in Fig. 4.

Table 1 shows the time-dependent temperature of the mold under the condition of compressed air cooling and water spray cooling. Checking point is the inner surface point of the mold at the farthest position from the coolant channel. The amplitude results of about 2.5℃ under the condition of 2 cases show that temperature condition of mold will not be changed much more when using water spray cooling instead of compressed air cooling.

Table 2 and Table 3 show time-dependent temperature of each position under the condition of compressed air cooling and water spray cooling. As shown in Table 2 and Table 3, the temperature results of the same position along the thickness direction of sheet at farthest and nearest from the coolant channel were nearly the same when the distance between channels in mass production was set as 125mm. Therefore, 1-D analysis can be used to simulate the cooling process of thermoforming for simplicity.

By comparing Table 2 and Table 3, it was found that water spray cooling can drop the temperature of the upper surface more quickly than compressed air cooling because of high cooling efficiency.

Table 1. Time-dependent temperature of mold.

Time	Air Cooling	Water Cooling
0s	80.00℃	80.00℃
8s	81.79℃	81.75℃
16s	82.60℃	82.51℃

Table 2. Time-dependent temperature using compressed air cooling.

Item	0s	8s	16s
Upper Surface (near from channel)	150℃	105.3℃	94.7℃
Upper Surface (far from channel)	150℃	105.5℃	94.9℃
Center (near from channel)	150℃	137.1℃	116.2℃
Center (far from channel)	150℃	137.3℃	116.3℃
Lower Surface (near from channel)	150℃	83.8℃	84.9℃
Lower Surface (far from channel)	150℃	84.1℃	85.1℃

3.2 Conversion from 2-D to 1-D problem

Previous 2-D analysis showed that 1-D analysis is possible. The equivalent heat transfer coefficient of coolant cooling from a 2-D to a 1-D problem must be calculated.

Shape factor(S) can be calculated by using Eq. 3. The distance between channels(P) was 125mm. The distance from upper surface of mold to the center of coolant channel(D) was 25mm. The calculated shape factor was 1.69.

$$S = \frac{2\pi}{\ln\left[\frac{2P}{D}\sinh\left(\frac{2\pi D}{P}\right)\right]} \tag{3}$$

Using Eq. 4, the calculated equivalent heat transfer coefficient of coolant conversion from 2-D to 1-D problem was 2.8424 $W/m^2 K$. The total length of channel(L) was 18.56m, and the diameter of channel(d) was 8mm. The thickness of mold was 25mm, and the surface dimension of sheet was 2×1 (m).

$$\frac{1}{\frac{D}{k}+\frac{1}{h_{w\_equivalent}}}\cdot(A_p) = \frac{1}{\frac{1}{\pi\cdot d\cdot h_w}+\frac{1}{S\cdot k}}\cdot(\pi\cdot d\cdot L) \tag{4}$$

3.3 1-D FDM analysis code

The total cooling cycle time was set as 35s, but real cooling time was 16s. In this cooling time, ABS sheet was cooled by compressed air cooling (or water spray cooling) and conduction, while the mold was cooled by conduction and coolant cooling for 16s. The other 19s was preparing time. In this period, ABS sheet is

Table 3. Time-dependent temperature using water spray cooling.

Item	0s	8s	16s
Upper Surface (near from channel)	150℃	46.0℃	40.3℃
Upper Surface (far from channel)	150℃	46.3℃	40.4℃
Center (near from channel)	150℃	126.5℃	99.3℃
Center (far from channel)	150℃	126.7℃	99.4℃
Lower Surface (near from channel)	150℃	82.2℃	83.0℃
Lower Surface (far from channel)	150℃	82.4℃	83.2℃

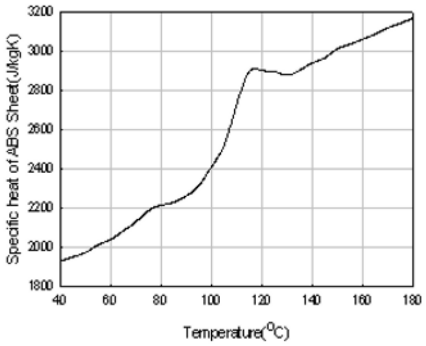

Fig. 5. Temperature-dependent specific heat of ABS.

cooled by convection, and mold is cooled by natural convection and coolant cooling.

Numerical simulation must be carried out to get the time-dependent distribution of temperature in the sheet because of temperature-dependent specific heat of ABS, as shown in Fig. 5[11].

FDM (finite difference method) was used to simulate the heat transfer. TDMA (tri-diagonal matrix algorithm) was used to solve the problem, and iterative calculation had to be carried out because of the temperature-dependent specific heat of ABS and coupling boundary condition between sheet and mold.

The governing equation, boundary condition and initial condition of sheet and mold are shown in Eq. 5 and Eq. 6, respectively. Where h_a is heat transfer coefficient of compressed air cooling or water spray cooling, h_c is heat transfer coefficient caused by contact resistance between sheet and mold, h_w is heat transfer coefficient of coolant, T_a is temperature in chamber, T_w is temperature of coolant, and k is thermal conductivity(W/m·K). The subscript p is ABS, m is mold, and i means initial value.

$$\begin{aligned} PDE: &\quad \rho_p C_p \frac{\partial T_p}{\partial t} = k_p \frac{\partial^2 T_p}{\partial x^2} \\ BCs: &\quad h_c[T_m(L_m,t) - T_p(0,t)] = -k_p \frac{\partial T}{\partial x} \\ &\quad h_a[T_p(L_p,t) - T_a] = -k_p \frac{\partial T}{\partial x} \\ IC: &\quad T_p(x,0) = T_{p\_i} \end{aligned} \tag{5}$$

$$\begin{aligned} PDE: &\quad \rho_m C_m \frac{\partial T_m}{\partial t} = k_m \frac{\partial^2 T_m}{\partial x^2} \\ BCs: &\quad h_c[T_p(0,t) - T_m(L_m,t)] = k_m \frac{\partial T}{\partial x} \\ &\quad h_w[T_m(0,t) - T_w] = k_m \frac{\partial T}{\partial x} \\ IC: &\quad T_m(x,0) = T_{m\_i} \end{aligned} \tag{6}$$

Table 4. Comparing between 2-D and 1-D analysis results.

Item	8s	16s
Upper Surface (2-D Analysis)	105.4℃	94.8℃
Upper Surface (1-D Analysis)	107.8℃	93.8℃
Center (2-D Analysis)	137.2℃	116.2℃
Center (1-D Analysis)	136.3℃	118.4℃
Lower Surface (2-D Analysis)	83.6℃	85.0℃
Lower Surface (1-D Analysis)	82.3℃	83.2℃

Table 5. Analysis conditions of 1-D FDM model.

Temperature of mold	90℃
Temperature of coolant	85℃
Initial temperature of sheet	150℃
Temperature in the chamber	30℃
Heat transfer coefficient caused by contact resistance	500W/m^2·K
Heat transfer coefficient of coolant	2.8424W/m^2·K
Heat transfer coefficient of compressed air cooling	100W/m^2·K
Heat transfer coefficient of water spray cooling	1000W/m^2·K
Heat transfer coefficient of transportation	10W/m^2·K

At first, 1-D analysis result was compared with 2-D analysis result in order to check the accuracy of the conversion from a 2-D to a 1-D problem. In 1-D analysis, h_c was given a big value in order to neglect contact resistance as in 2-D analysis. By comparing, it was found out that 1-D analysis code is suitable for analyzing the cooling system of thermoforming in certain accuracy as shown in Table 4. 2-D analysis results shown in Table 4 are the mean value of each surface.

4. Specification of 1-D analysis condition

Table 5 shows the analysis conditions. The temperature of mold and coolant are the average data of mass production. The temperature of mold must be kept on the temperature shown in Table 5 because it is the most suitable temperature for forming products. The heat transfer coefficient of transportation was assumed a little larger than the mean value of natural convection because the product on the moment of forming is happened overturning during transportation[12, 13].

Table 6 and Table 7 show time-dependent mean

Table 6. Time-dependent mean temperature of ABS sheet under 3 different conditions.

On the moment	Air (16s)	Water (16s)	Water(7s) + Air(9s)
7s	131.5℃	114.6℃	114.6℃
16s	116.5℃	93.7℃	113.8℃
35s	109.4℃	88.8℃	97.7℃

Table 7. Time-dependent temperature of mold under 3 different conditions.

On the moment	Air (16s)	Water (16s)	Water(7s) + Air(9s)
7s	91.2℃	91.2℃	91.2℃
16s	92.1℃	92.0℃	92.0℃
35s	91.8℃	91.7℃	91.7℃

temperature of ABS sheet and temperature of mold at specified time under the condition of compressed air cooling, water spray cooling and the combined water and air cooling, respectively.

As shown in Table 6, water spray cooling can drop the surface temperature faster than the others because of high cooling efficiency.

Table 7 shows that mold temperature will not be changed much more when the other cooling method is applied. This is very important because mold must be modified if the temperature condition is changed much more.

The total energy removed from the sheet can be calculated by using Eq. 7. Where V_p is volume of sheet(m^3)

$$Q_{removed} = \rho \cdot V_p \cdot C_p \cdot (T_{f\_mean} - T_i) \quad (7)$$

The removed energy from the upper surface of sheet can be calculated by Eq. 8.

$$Q = A_p \cdot \int_0^{16} q(T)dT \quad (8)$$

The calculated ratio of the energy removed from upper surface among the total removed energy under the three different conditions is shown in Table 8. The efficiency of water spray cooling was the best one of the three different conditions, but the merit of the combination of water and air cooling is that it can remove the rest of the sprayed water droplets with good cooling efficiency. Also, the cooling efficiency of water spray is not so high when the temperature of the sheet surface is lower than the saturation temperature, so the combination of water spray cooling and compressed air cooling is the best candidate.

Table 8. Calculation of the ratio removed from upper surface of sheet under the 3 different conditions.

Item	Air (16s)	Water (16s)	Water(7s) + Air(9s)
Total Removed Energy	0.645MJ	0.973MJ	0.831MJ
Upper Surface	0.250MJ	0.566MJ	0.420JM
Ratio(%)	38.7	58.1	50.5

If the parameters of spray cooling such as velocity of droplet, diameter of droplet etc. are adjusted, the efficiency of the cooling can be improved[14].

The 1-D analysis code can be widely used in the design of a thermoforming cooling system, and parameters of the thermoforming process can be modified based on the recommended data suitable for the cooling system of thermoforming.

5. Conclusions

The analysis code which can be used to simulate the process of cooling has been developed. In order to shorten cycle time and reduce the cost of production, water spray cooling was simulated to apply to the cooling system of thermoforming. To check the state of mass production, cooling time using compressed air was predicted at first. To compare the cooling efficiency of compressed air cooling and water spray cooling, the ratio of removed energy from upper surface of sheet among the total removed energy was calculated by using the developed 1-D analysis code of the cooling process under the condition of checking the accuracy of 1-D analysis code by comparing with the 2-D result. The analysis results using water spray cooling show that cycle time can be reduced because of high cooling efficiency of the water spray, and the cost of production can be reduced by decreasing the amount of the compressed air used.

Nomenclature

A : Area, m^2
C_p : Specific heat, kJ/kgK
d : Diameter of coolant channel, m
D : Distance between center of coolant channel and upper surface of mold, m
h : Heat transfer coefficient of convection,

W/m^2K
h_{fg} : Latent heat of water, 2257kJ/kg
k : Thermal conductivity, W/mK
L : Total length of coolant channel, m
m : Mass, kg
$\dot{m}$: Mass flow rate, kg/s
P : Distance between channels, m
q : Heat flux, W/m^2
Q : Heat flow rate, W
S : Shape factor
t : Time, s
T : Temperature, ℃
Th : Thickness, m

Greek Symbols

ρ : Density, kg/m^3

Subscript

a : Air
c : Contact
cl : Cooling
e : Environment
f : Final
i : Initial
m : Mold
p : Sheet
w : Water

References

[1] M. K. Warby, J. R. Whiteman, W. G. Jiang, P. Warwick and T. Wright, Finite element simulation of thermoforming processes for polymer sheets, *Mathematics and Computers in Simulation* 61 (3-6) (2003) 209-218.

[2] J. L. Throne, *Technology of Thermoforming*, Hanser Publishers, Munich, New York, USA, (1987).

[3] G. Aguilar, B. Majaron, K. Pope, L. O. Svaasand, E. J. Lavernia and J. S. Nelson, Influence of nozzle-to-skin distance in cryogen spray cooling for dermatologic laser surgery, *Lasers in Surgery and Medicine* 28 (2) (2001) 113-120.

[4] Q. Cui, S. Chandra and S. McCahan, The effect of dissolving salts in water sprays used for quenching a hot surface. Part 2: spray cooling, *Journal of Heat Transfer* 125 (2) (2003) 333-338.

[5] Y. Mitsutake, M. Monde, Y. Kojima and A. Mikami, Characteristics of transient heat transfer on a hot surface during cooling with spray, *Thermal Science and Engineering* 12 (4) (2004) 41-42.

[6] J. A. Clements and S. A. Sherif, Thermal analysis of roof spray cooling, *International Journal of Energy Research* 22 (15) (1998) 1337-1350.

[7] S. S. Hsieh, T. C. Fan and H. H. Tsai, Spray cooling characteristics of water and R-134a. Part I: nucleate boiling, *International Journal of Heat and Mass Transfer* 47 (26) (2004) 5703-5712.

[8] J. Yang, L. C. Chow and M. R. Pais, Nucleate boiling heat transfer in spray cooling, *Journal of Heat Transfer* 118 (3) (1996) 668-671.

[9] F. P. Incropera and D. P. Dewitt, *Fundamental of Heat and Mass Transfer*, John Wiley & Sons, New York, USA, (1996).

[10] A. Bejan, *Convection Heat Transfer*, John Wiley & Sons, New York, USA, (1995).

[11] Z. Z. Li, K. S. Heo and S. Y. Seol, Time-dependent optimal heater control in thermoforming preheating using dual optimization steps, *International Journal of Precision Engineering and Manufacturing* 9 (4) (2008) 51-56.

[12] R. J. Goldstein, E. M. Sparrow and D. C. Jones, Natural convection mass transfer adjacent to horizontal plates, *Int. J. Heat and Mass Transfer* 16 (1973) 1025-1037.

[13] J. R. Lloyd and W. R. Moran, Natural convection adjacent to horizontal surfaces of various plan forms, *Journal of Heat Transfer* 96 (1974) 443-451.

[14] B. M. Pikkula, J. W. Tunnell, D. W. Chang and B. Anvari, Effects of droplet velocity, diameter, and film height on heat removal during cryogen spray cooling, *Annals of Biomedical Engineering* 32 (8) (2004) 1131-1140.

Zhen-Zhe Li received his B.S. degree in Mechanical Engineering from Yanbian University, China, in 2002. He then received his M.S. degree in Aerospace Engineering from Konkuk University, South Korea, in 2005. He then received his Ph.D. degree in Mechanical Engineering from Chonnam National University, South Korea, in 2009. Dr. Li is currently a Researcher of the Department of Mechanical Engineering, Chonnam National University, South Korea. Dr. Li's research interests include applied heat transfer, fluid mechanics and optimal design of thermal and fluid systems.

Kwang-Su Heo received his B.S. degree in Mechanical Engineering from Chonnam National University, South Korea, in 1998. He then received his M.S. and Ph.D. degrees in Mechanical Engineering from Chonnam National University, South Korea, in 2003 and 2008, respectively. Dr. Heo is currently a Post-doctorial Researcher of the Department of Mechanical Engineering, KAIST(Korean Advanced Institute of Science and Technology), South Korea. Dr. Heo's research interests include applied heat transfer, fluid mechanics and thermal analysis of superconductor.

Dong-Ji Xuan received his B.S. degree in Mechanical Engineering from Harbin Engineering University, China, in 2000. He then received his M.S. degree in Mechanical Engineering from Chonnam National University, South Korea, in 2006. He is currently a Ph.D. candidate of the Department of Mechanical Engineering, Chonnam National University, South Korea. His research interests include control & optimization of PEM fuel cell system, dynamics & control, mechatronics.

Seoung-Yun Seol received his B.S. degree in Mechanical Design from Seoul National University, South Korea, in 1983. He then received his M.S. degree in Mechanical Engineering from KAIST(Korean Advanced Institute of Science and Technology), South Korea, in 1985. He then received his Ph.D. degree in Mechanical Engineering from Texas Tech University, USA, in 1993. Dr. Seol is currently a Professor of the School of Mechanical and Systems Engineering, Chonnam National University, South Korea. Dr. Seol's research interests include applied heat transfer, fluid mechanics and thermal analysis of superconductor.