THERMAL ANALYSIS OF ROTATIONAL MOULDING PROCESS: AN APPLICATION TO MULTILAYER MOULDING

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ABSTRACT

Rotational Moulding is one of the fastest growing technologies in the processing of thermo-plastics. Multilayer products obtained by this process find extensive application in automobile components, particularly in fuel tanks. The process is characterized by a complex nature of heat transfer involving several phase changes. This paper presents a transient thermal simulation of the process for multilayer moulding of Linear Low Density Polyethylene (LLDPE) and Polyamide -11 (PA-11). FEM based COMSOL software is used for analysis and Heaviside function is used to model the phase changes over a range of temperatures. The cycle time, time required for phase transitions, time required for optimal curing temperature and demoulding time have been found out. It takes approximately 66 minutes to complete the cycle. The study can be useful to rightly tune the process to achieve the optimal quality characteristics of the part with reduced energy consumption.

Keywords: LLDPE, PA-11 and Heaviside Function

1. Introduction

Rotational Moulding is a polymer processing technology used for producing hollow seamless articles by heating, melting and subsequent sintering of powders in bi-axially rotating moulds, followed by cooling the melt for solidification. The products obtained by rotational moulding provide the best amalgam of good engineering and ergonomic design, apart from many other inherent advantages in terms of mechanical properties and low tooling costs. With significant growth rate in India's infrastructural requirements, the products obtained by rotational moulding have gained considerable importance in applications like underground systems of storage e.g. rainwater harvesting, disposal of gray and black water, sanitation, waste management, etc. Apart from this, the automobile sector is looking towards this process as one of the potential process to produce hollow complex shaped parts (like a fuel tank), at lesser costs. One of the drawbacks of this process is entrapment of bubbles of gases during sintering that reduces the mechanical strength of the product. Such problems can be attributed to complex nature of heat transfer during this process, in spite of its apparent simplicity. It was found that Mechanical properties of rotationally moulded product depend on Peak Internal Air Temperature (PIAT) of the mould (Crawford and Nugent, 1992). As a rule, a PIAT of 200^0C has been recommended for optimal curing of the rotationally moulded parts. As rotational moulding suffers from a relatively long cycle time, the importance of internal cooling of the mould is emphasized (Tan et al., 2011). To prevent any significant polymer thermal degradation of polypropylene during rotational moulding, a model including thermal and chemical regions is suggested (Sarrabi et al., 2010). The simulation of 1-Dimensional unsteady heat transfer during rotational moulding has been done using statistical and kinetic models (Greco *et al.,* 2003, 2004). Theoretical and numerical models have been proposed to model the heat transfer phenomena in rotational moulding (Gogos *et al.,* 1998). Several analytical studies can be found that correlate the phase changes during the process with the experimental findings. From the literature, it is evident that during the complex nature of heat transfer involving phase as well as density changes, molten polymer is in high viscous state for a long time to remove any entrapped bubbles. Since the phase change occurs over a range of temperature the assumption of the same at one particular temperature often results in errors in predictions. The situation becomes more complex when a multilayer moulding like that of LLDPE and Nylon (PA-11) has to be carried out. Further, Owing to the bi-axial nature of mould rotation, there is a dearth of accurate thermal data measurement techniques and equipment that can ascertain the exact temperature at the various time states at different points in the mould. Thus, there is an imperative need to perform a thermal analysis of the process by simulating a virtual model to ascertain the

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most optimum situation and way of carrying out this process in the most cost-effective way whilst obtaining premium product quality. This paper presents the findings of the simulation studies for the process. For this purpose, a transient thermal analysis was carried out using FEMLAB based software COMSOL. To model the phase change over a range for a multilayer moulding, a Heaviside function is used. Using this, attempts were made to obtain the temperatures of air inside the mould and time required to reach PIAT of 200^0C.

2. Methodology

2.1 Physical model

For this study, we have chosen a product having external dimensions as 100 mm x 100 mm with a multilayer moulding of LLDPE having outside thickness of 5 mm and PA-11 having inside thickness of 2 mm. Such multilayer mouldings made by rotational moulding are now recommended for automobile fuel tanks (Brien et al., 2004, Carlson and Partridge, 2007). The inner layer of PA-11 is preferred owing to its excellent barrier properties (impermeability to the fuel vapours) along with good mechanical properties. Fig. 1 shows the model chosen for analysis.
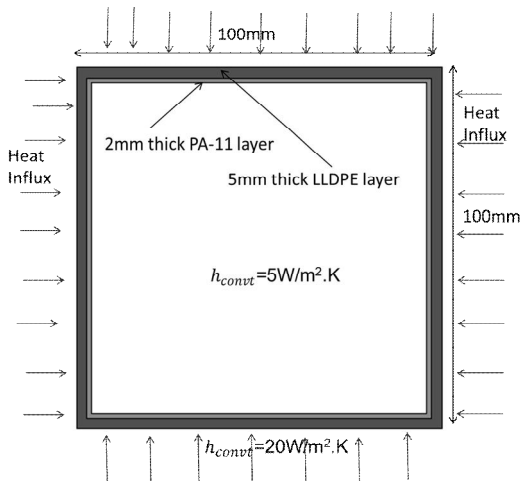

Fig. 1 Physical Model Chosen for Analysis

To obtain this product, an Aluminium mould of 5mm thickness is chosen. For analysis, advantage is taken of the reflection symmetry of the mould. Also, as the speed of rotation of the mould is very less (around 20 rpm), the heat transfer process can be studied assuming 'static' model of the process. Similar assumptions have been made by Gogos et al. (1998). The heat transfer is modeled in three stages; first

convective heating of the mould in oven kept at 300^0C (573^0K) till the melting temperature of LLDPE, followed by phase change of the LLDPE and PA-11 and subsequent heating of the air ahead of the polymer layers and cooling of the entire mass after the PIAT of 200^0C (473^0K) is attained. The physical model and corresponding boundary conditions chosen for the analysis are also shown in Fig. 1. It can be noted that the inner boundaries of LLDPE, PA-11 and internal air have been set to continuity. The condition implies that conduction is allowed to occur across these boundaries according to the conduction coefficients chosen.

2.2 Governing equations and application of heaviside function in analysis

To model the transient heat transfer phenomenon, Fourier heat conduction equation is chosen (Incropera et al., 2006). In present analysis it takes the form as shown in Eq. (1):

$$\delta_{ts} C_{eq} \cdot \frac{\partial T}{\partial t} - \nabla \cdot (K_{eq} \nabla T) = Q_G + Q_C + Q_R \qquad (1)$$

where T =Temperature, δ_{ts} = Time Constant,
K_{eq} = Equivalent Thermal Conductivity, $\sum(\theta K)/\sum\theta$
C_{eq} = Equivalent Specific heat = $\sum(\theta \rho C_p)/\sum\theta$,
Q_C=Heat transferred by convection = $h_{trans}(T_{ext} - T)$
Q_R =Heat transferred by radiation= $C_{trans}(T_{trans}^4 - T^4)$, θ=Liquid volume fraction

In this analysis, heat transfer owing to radiation has been neglected with no internal heat generation. As the melting and solidification takes place over a range in the vicinity of melting and solidification temperatures, the Heaviside Function was chosen for implementing the change in volume fraction of fluid state of the polymer (Bracewell, 2000). This is a discontinuous function whose value is zero for negative argument and one for positive argument. Thus, the Heaviside Function can be made to be zero for the temperature less than the melting point of the resin and 1 for temperature greater than melting point. It may be piecewise or point-wise continuous and is given as:

$$H(x) = \int_{-\infty}^{x} \delta(t)dt \qquad (2)$$

Where δ is the Dirac delta function which is characteristically 0 for all values in the interval except 0 itself where it assumes the value infinity. Smooth continuous form of this function has been assumed as piece-wise continuous as:

$$H(x) = \frac{1}{1+e^{-kx}} \qquad (3)$$

Assuming that the phase process commences 5K before the temperature of the material reaches transition temperature (T_{trans}) and ends 5K after T_{trans}. Hence, the entire fusion process actually gets

completed over a temperature interval range of 10K. Table 1 shows the Heaviside function values for different states of the polymer.
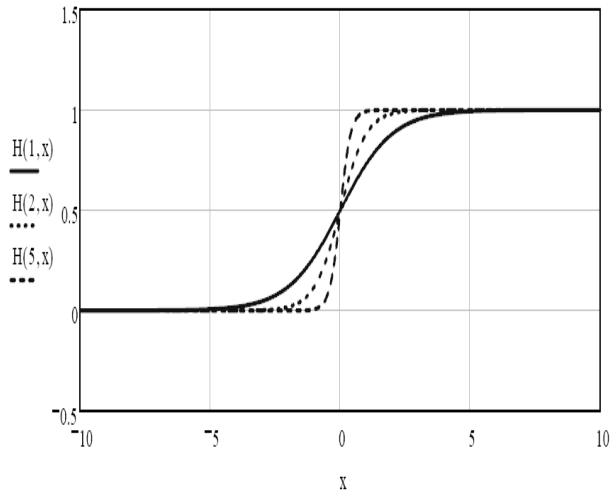

Fig. 2 A piece-wise Continuous Approx. of Heaviside Function

Table 1: Heaviside Function Scenarios

Condition	Heaviside Function Value	Volume Fraction of Fluid Sate
$(T - T_{trans}) < -dT$	0	0
$-dT < (T - T_{trans}) < dT$	0<H<1	H
$(T - T_{trans}) > dT$	1	1

For implementing the latent heat of fusion gradually with phase change, the differential of the Heaviside Function with respect to Temperature at that instant was considered and further integrated over the entire interval of phase change since the Heaviside function has been assumed to be piece-wise continuous for this model. This can be written as:

$$C_{eq} = C_p + \int_{-dT}^{dT} \frac{\partial H}{\partial T} * lm \qquad (4)$$

where C_{eq} is the equivalent specific heat capacity of the polymer and lm is the Latent Heat of fusion. The variables and constants used for analysis are shown in Table 2 while material properties and other variables used for the analysis are listed in Table 3.

Table 2: Variables & Constants used

Constant/Variable	Expression	Description
T_{trans}	401K	Melting Point of LLDPE
dT	5K	Temperature Half Interval for Heaviside Function
$lm1$	180KJ/Kg	Latent Heat of Fusion of LLDPE
$lm2$	78.1 KJ/Kg	Latent Heat of Fusion of PA-11
$D1$	$\partial H/\partial T$	For effective specific heat capacity of LLDPE
$D2$	$\partial H/\partial T$	For effective specific heat capacity of PA-11

3. Results & Discussions

To monitor the temperature changes during the first phase of the process, two points were considered, one within the LLDPE layer and the other in the internal air. The transient temperature distribution at these points is shown in Fig. 3. It can be observed that the temperature rises steadily till 396K where LLDPE starts melting. This phase change can be seen as reduction in slope of the Temperature-Time curve. The first phase is continued till the time the entire LLDPE powder has melted. The flatness in curve can also be observed in air temperature as well, owing to unavailability of heat to raise temperature during melting of LLDPE.

Table 3: Material Properties

| Sub Domain Property	Unit	Aluminium	LLDPE	PA-11	Air
Internal Convective Heat Transfer Coefficient	W/ (m²·K)	-	-	-	5
External Air Convective Heat Transfer Coefficient	W/m² K			-	20
Equivalent Specific Heat Capacity	KJ/Kg K	900	2430+$D1*lm1$	1675+$D2*lm2$	1.006
Density (Liquid State For LLDPE)	Kg/m³	2700	932	1150	1.205
Density (Initial Amorphous Form Of LLDPE)	Kg/ m³	2700	400	400	1.205
Thermal Conductivity	W/m.K	214	0.2	0.27	0.025
Initial Temperature	K	298	298	298	298
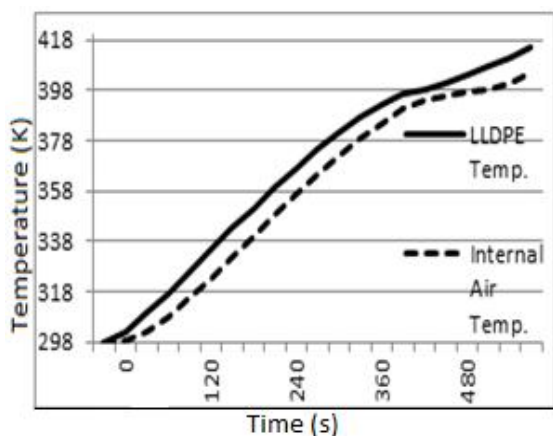
Fig. 3 Tranisent Temperature within the Mould

Fig. 4 shows the change in volume fraction of the fluid state of LLDPE and depicts the phase change more explicitly. It can be seen that till 420s volume fraction of its fluid state was zero, which augmented steadily till all the LLDPE has been completely melted at 540s when temperature was 406K.

In multilayer moulding, second layer is added as soon as the first layer is formed by melting, i.e. 540 s in present case. To simulate this, we have taken 2mm layer of PA-11 powder which corresponds to a mass of 0.7176 Kg. Properties of PA-11 are enlisted in Table-3.
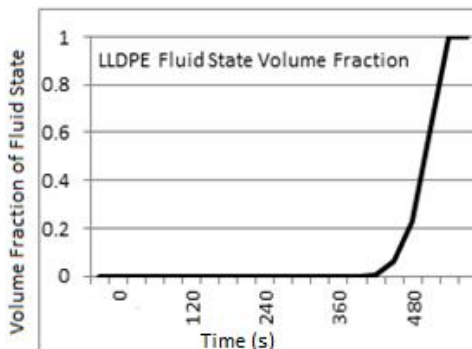

Fig. 4 Change in Volume Fraction of Liquid State of LLDPE over Time

As PA-11 (which was at room temperature initially) comes in direct contact with the LLDPE from one side and internal air from the other, it absorbs heat from both sides. This results in large temperature gradients which could be seen as as massive temperature differences of 108^0 C with internal air (and PA-11) and of 134^0 C with LLDPE (and PA-11). As a result the temperature of PA-11 rises in 30s (very quickly), to establish the thermal equilibrium. It starts melting at 460K around 610 S. Fig. 5 depicts the reduction in temperatures of LLDPE and internal air upon addition of PA-11. It can also be seen that as soon as the thermal equilibrium is established, the rise in temperature continues. Cooling of the mould commences after an optimal curing temperature of 473 ^{0}K is reached. To simulate the cooling process, the conditions arrived at 473K were taken as initial conditions.
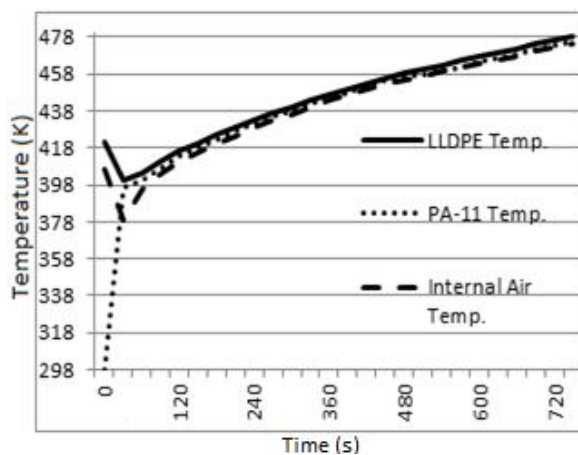

Fig. 5   Transient Temperature Distribution after Adding PA-11

Fig. 6 shows the phase change of PA-11 during its solidification. The cooling of entire mould involving LLDPE, PA-11 and internal air can be seen in Fig. 7. The phase changes of LLDPE and PA-11 taking place over the entire rotational moulding cycle as discussed above are shown in Fig. 8. The transient temperature distribution for the entire cycle is depicted in Fig. 9. A cycle time of almost 4000 S was observed for the process. Efforts are being made to reduce such large cycle times by making the provisions like extended surfaces (fins) on mould as well as internal pressuring of the mould with cold air, to make the process competitive with the other processes like blow moulding, injection moulding, etc. The findings obtained here are in agreement with the experimental findings reported elsewhere in literature (e.g. Crawford and Nugent, 1992), which validates the methodology adapted.
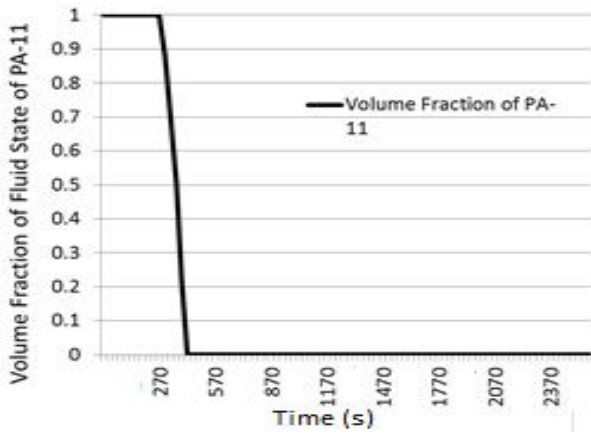

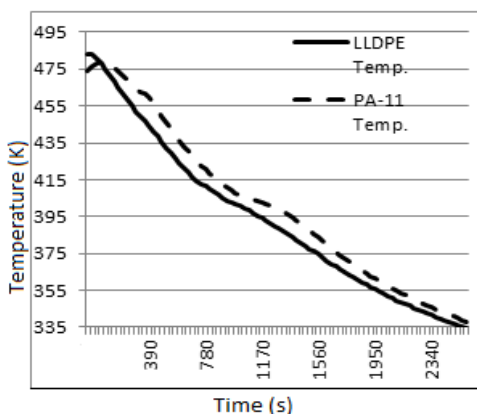**Fig. 6   Change in Volume Fraction of Liquid State of PA-11 over Time**

Fig.7 Transient Temperature Distribution during Cooling
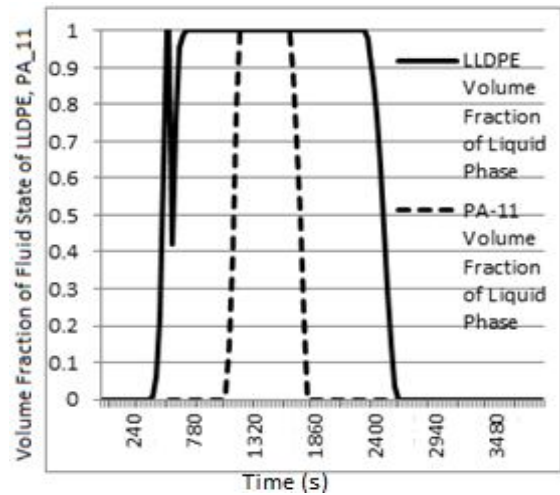

Fig. 8   Volume Fraction of Fluid States for Entire Process

4. Conclusions

In this paper, an attempt has been made to simulate the thermal transitions that take place in rotational moulding process. The analysis has been carried out for a multilayer moulding of LLDPE/PA-11. It was found that melting of LLDPE started around 420 S which got completed around 540 S. When the second layer of PA-11 was added, a sudden drop in temperature was observed and severe thermal gradients were seen. It took almost 1410 S to reach the optimal curing temperature of the polymers. Phase transitions of the polymer were seen during solidification and it took almost 4000 S to complete the entire cycle. The simulation is useful to predict the critical timings of the process like switching off the oven which can pave new ways to economize the energy inputs to the processes save significant energy as well as time. Also the conditions for optimal curing can be predicted to get consistent mechanical properties. Owing to the large thermal gradients in the process, such studies can be useful to model and study the phenomena like warpage of parts which are common in mouldings particularly of large thickness. Further, the simulation can be equally useful if any new materials need to be tested for the rotational moulding process. The simulation can be mapped to any geometry to predict all of the above mentioned characteristics for varying polymers and can be changed as per design and production requirements for various products capable of production using rotational moulding Process.
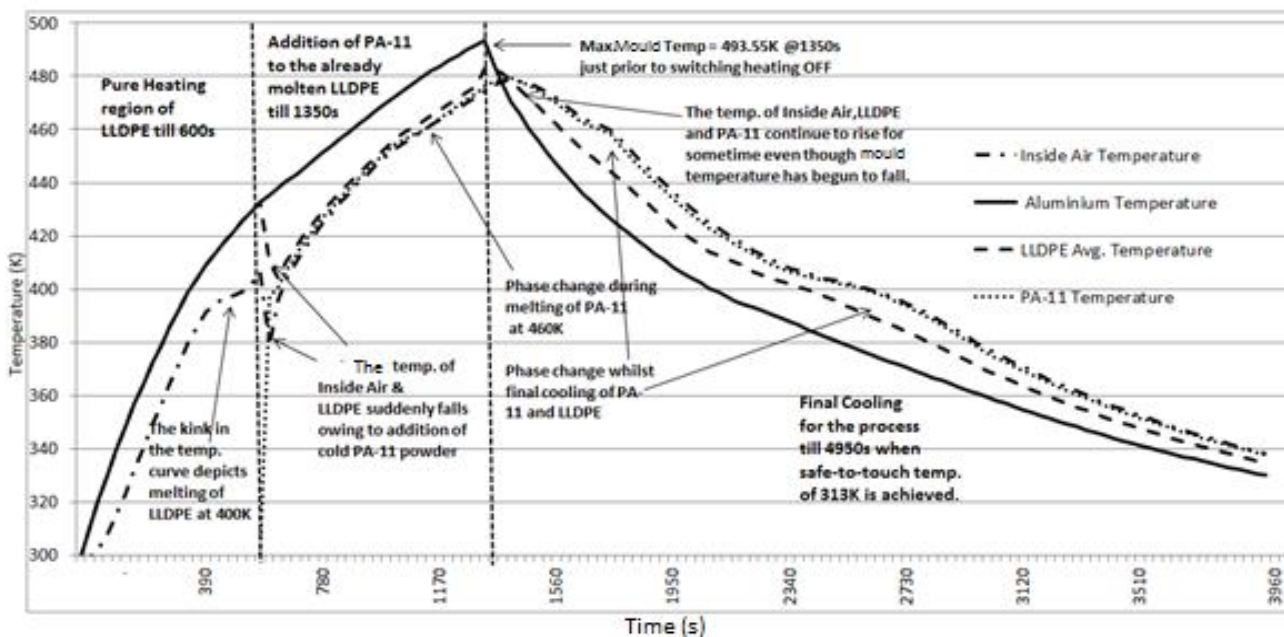
Fig. 9 Transient Temperature Distribution over Entire Rotational Moulding Cycle

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Nomenclature

Symbol	Meaning	Unit
T	Temperature	K
K_{eq}	Equivalent Thermal Conductivity	W/m.K
C_{eq}	Equivalent Specific Heat Capacity	KJ/Kg.K
Q_C	Heat transfer due to convection	W
h_{trans}	Convective Heat Transfer Coefficient	$W/(m^2 K)$
C_{trans}	Radiation Heat Transfer Coefficient	$W/(m^2 K^4)$
T_{trans}	Temperature of transient surroundings	K
Q_R	Heat transfer due to Radiation	W
Lm1	Latent Heat of LLDPE	KJ/Kg
Lm2	Latent Heat of PA-11	KJ/Kg
D1	Effecting Latent Heat of LLDPE	1/K
D2	Effecting Latent Heat of PA-11	1/K