World Academy of Science, Engineering and Technology
International Journal of Chemical and Molecular Engineering
Vol:9, No:10, 2015

Visualization of Flow Behaviour in Micro-Cavities during Micro Injection Moulding

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Abstract**—**Polymeric micro-cantilevers (Cs) are rapidly becoming popular for MEMS applications such as chemo- and bio-sensing as well as purely electromechanical applications such as microrelays. Polymer materials present suitable physical and chemical properties combined with low-cost mass production. Hence, micro-cantilevers made of polymers indicate much more biocompatibility and adaptability of rapid prototyping along with mechanical properties. This research studies the effects of three process and one size factors on the filling behaviour in micro cavity, and the role of each in the replication of micro parts using different polymer materials i.e. polypropylene (PP) SABIC 56M10 and acrylonitrile butadiene styrene (ABS) Magnum 8434 . In particular, the following factors are considered: barrel temperature, mould temperature, injection speed and the thickness of micro features. The study revealed that the barrel temperature and the injection speed are the key factors affecting the flow length of micro features replicated in PP and ABS. For both materials, an increase of feature sizes improves the melt flow. However, the melt fill of micro features does not increase linearly with the increase of their thickness.

Keywords**—**Flow length, micro-cantilevers, micro injection moulding, microfabrication.

I. INTRODUCTION

ONE of the key technologies for the production of micro/nano-structured components is micro injection molding which is a well-known method for fabricating micro parts made of polymers. The definition of micro injection molding is as follows [1]:

- Parts with overall sizes of less than 1 mm
- Parts with overall dimensions larger than 1mm but incorporate micro features with sizes typically smaller than 200 µm
- Parts of any dimension including a mass of the order of a few milligrams, but the feature tolerances are required to be in the µm range
- Parts possessing a weight in the range of a few milligrams

A number of commercial CAE packages such as C-Mold and Moldflow have become the accepted part of process simulation. Moldflow package applies two major models in order to simulate the processes which are Hele-Shaw model and Navier-Stokes model [2]. Griffiths et al. [1] studied the flow behavior of polymer melts in micro cavities by Moldflow Plastics Insight software and then validated against the experimental results of the study [3]. They used two FEA models i.e. the orthogonal element and the tetrahedral element mesh models to carry out a dual-domain analysis and a 3D analysis respectively. The dual-domain flow analysis overestimated the polymer flow length in all simulation runs. The 3D flow analysis underestimated the polymer flow length in PP simulation runs. However, for ABS there was both an overestimation and underestimation of the flow lengths. Overall, 3D simulations for both materials were closer to the actual results. In this study, a model for simulating the flow behavior of polymer melts in micro-cantilevers is reported. The model was developed within the Moldflow Plastics Insight software. By using design of experiments method (DOE), a serious of simulation runs was carried out to analyze the effects of a range of process variables on the filling behavior. Finally, conclusions are made about the accuracy and sensitivity of the proposed simulation model.

II. SIMULATION MODEL

The finite element method (FEM) was employed in this research to create a model for simulating the polymer filling behavior in micro-cavities. The CAD model of the part once imported and meshed as shown in Fig. 1, is used for dual domain analysis of laminar flow in generalised Newtonian fluids utilising the Hele-Shaw flow model. The material flow front begins from the injection node and is then calculated throughout the model using a three node triangular mesh as illustrated in Fig. 2. Particularly, the flow front propagates by repeatedly filling and adding further nodes [1]. In addition, a tetrahedral element mesh was applied to the model in order to perform a three-dimensional (3D) analysis based on the Navier-Stokes flow model [2]. There are two test part consist of cantilevers 4 mm long, 500 µm wide with different micro features thickness in a 25x25x1 mm thick carrier. The thickness of micro features in first part is 30 µm while it is 120 µm in the second test part.

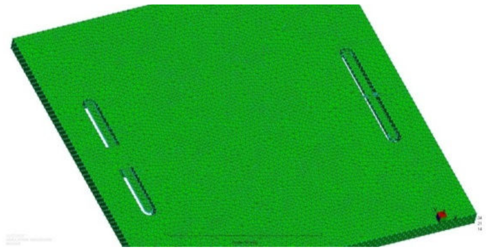

Fig. 1 The CAD model meshed

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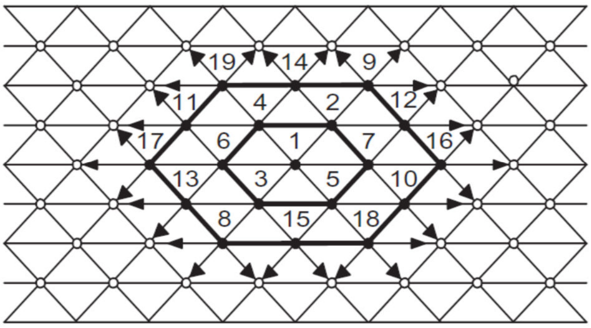


Fig. 2 A three node triangular mesh [1]

To simulate the polymer flow behaviour the Cross WLF model is applied [4]. The Cross-WLF model is a function of temperature and pressure and is considered to be more effective in comparison with the power law model [5]. By implementing this viscosity model, it was possible to carry out both temperature and pressure related simulation analyses. Some key process factors such as injection time (t_i), melt temperature (T_b) and mould temperature (T_m) are required to be defined for analyzing the model dependency on temperature and pressure in each simulation run. Then, the created model is used to investigate the flow behaviour.

III. DESIGN OF EXPERIMENTS (DOE)

To study the effects of µIM process factors on the melt flow behaviour this experimental investigation was focused only on the filling stage of the process using dual-domain model. The filling performance of micro cavities relies heavily on the speed and the temperature control during injection. Therefore in addition to thickness of cantilevers (D) the effects of T_b, T_m, V_i were investigated. In this research, the full-factorial design was applied for each investigated material. Given that four factors at two levels were considered as presented in Table I. Regarding V_i, two levels i.e. 200 and 800 mm/s were set to conduct the experiments but it was not possible to utilize the same values in the simulation runs and therefore they were replaced with injection time control parameters t_i 0.5 and 0.1 s, respectively. The two levels of control for D and t_i were the same for all materials, while the levels for T_b and T_m were different.

Given that two different materials, a two-level four-factor randomized full factorial design was defined. The response variable considered is flow length.

TABLE I
PROCESS PARAMETERS

Polymer	Level	T_b [˚C]	T_m [˚C]	V_i [mm/s]	D [µm]
PP	−	210	10	200	30
	+	270	70	800	120
ABS	−	210	30	200	30
	+	270	90	800	120

IV. ANALYSIS OF THE DOE RESULTS

In this research, the Minitab 17 software was used to carry out the statistical analysis of the results. Significant effects were studied depending on the average aspect ratios achievable for each combination of control parameters. The influence of investigated factors was estimated using the normal probability plots of these effects. By employing DoE this study can be used further to optimize the process by identifying the best combination of processing parameters, and also the most significant of them in regards to the flow length performance. The achieved aspect ratios for each combination of parameters are shown in Table II.

TABLE II
ACHIEVED ASPECT RATIOS FOR PP AND ABS

RUN	Factors				Aspect Ratio	
	T_b	T_m	V_i	D	PP	ABS
1	−	+	−	+	5.06	4.87
2	−	−	−	+	4.81	4.93
3	−	+	−	−	0.18	0
4	+	−	+	+	5.62	5.50
5	+	−	−	−	0	0
6	−	+	+	+	5.68	5.31
7	−	−	+	−	0.12	0.12
8	+	+	−	−	4.06	0.06
9	+	−	+	−	4.43	0.06
10	+	+	+	−	0	0.18
11	+	+	+	+	5.81	5.68
12	−	+	+	−	0	0.06
13	+	−	−	+	5	5
14	−	−	−	−	0.12	0
15	−	−	+	+	5.43	5.18
16	+	+	−	+	5.18	5.12

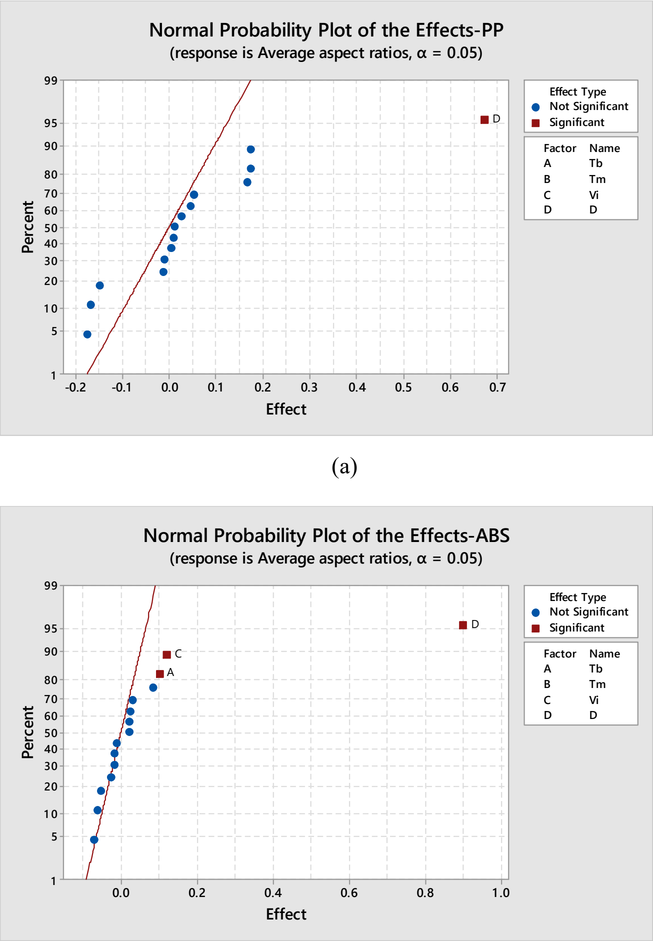
The investigated factors, T_b, T_m, V_i and D are represented as parameters A, B, C and D, respectively, in DoE. The effects of them for PP and ABS are shown in Figs. 3 (a) and (b), respectively.

The results show that D was a very important factor in improving the melt fill of micro features for both PP and ABS. In addition, by increasing T_b and V_i, higher aspect ratios were achieved for ABS. However, the responses were not consistent throughout the experiments as it is shown in Table II. For both PP and ABS, the interaction of parameters shows an insignificant effect on the achievable aspect ratios. In case of PP, it had even a negative effect on the melt fill. In the most of combinations melt flowed into the micro cantilevers except those with depth of 30 µm replicated with low process settings.

Figs. 3 (a) and (b) also show that generally D had a larger effect on the melt fill than any other parameter; however this relationship is not linear. Another important observation is that in most cases the micro cantilevers along the melt flow are filled better at the higher settings of T_b and V_i as the data in Table II indicates.

The settings that led to maximum flow length in the moulding trials in Table II are provided in Table III. In particular, R1 and R3 correspond to the PP and ABS maximum flow length settings for mould insert with 30 µm depth, respectively, while R2 and R4 to the maximum flow length achieved for both PP and ABS with 120 µm depth.

Open Science Index, Chemical and Molecular Engineering Vol:9, No:10, 2015 publications.waset.org/10002422.pdf



(a)

(b)

Fig. 3 Analysis of the results for (a) PP and (b) ABS

V. SIMULATION OF FLOW LENGTH

In Table IV, the obtained maximum flow lengths for both materials, PP and ABS using the dual domain and 3D simulation analyses are reported.

R1 and R3 correspond to mould inserts including micro features with 30 µm depth leading to maximum flow length, while R2 and R4 represent the maximum flow length of inserts collaborating features with 120µm depth for PP and ABS, in the experimental study, respectively (Figs. 4-7).

The dual domain results as they are depicted in Fig. 4 shows that the mould cavity could not be filled completely in both simulation runs because the melt is unable to flow into the micro features. In the case of PP, melt slightly goes into the micro feature but short after melt advance stops due to significant reduction of melt front temperature (T_{ff}) which range from 270 to 150˚C. Although for ABS the variation of T_{ff} is less than PP which is in the range of 270 to 200 ˚C, the molten material cannot pass through the micro features. It can be explained by higher viscosity of ABS comparing to PP.

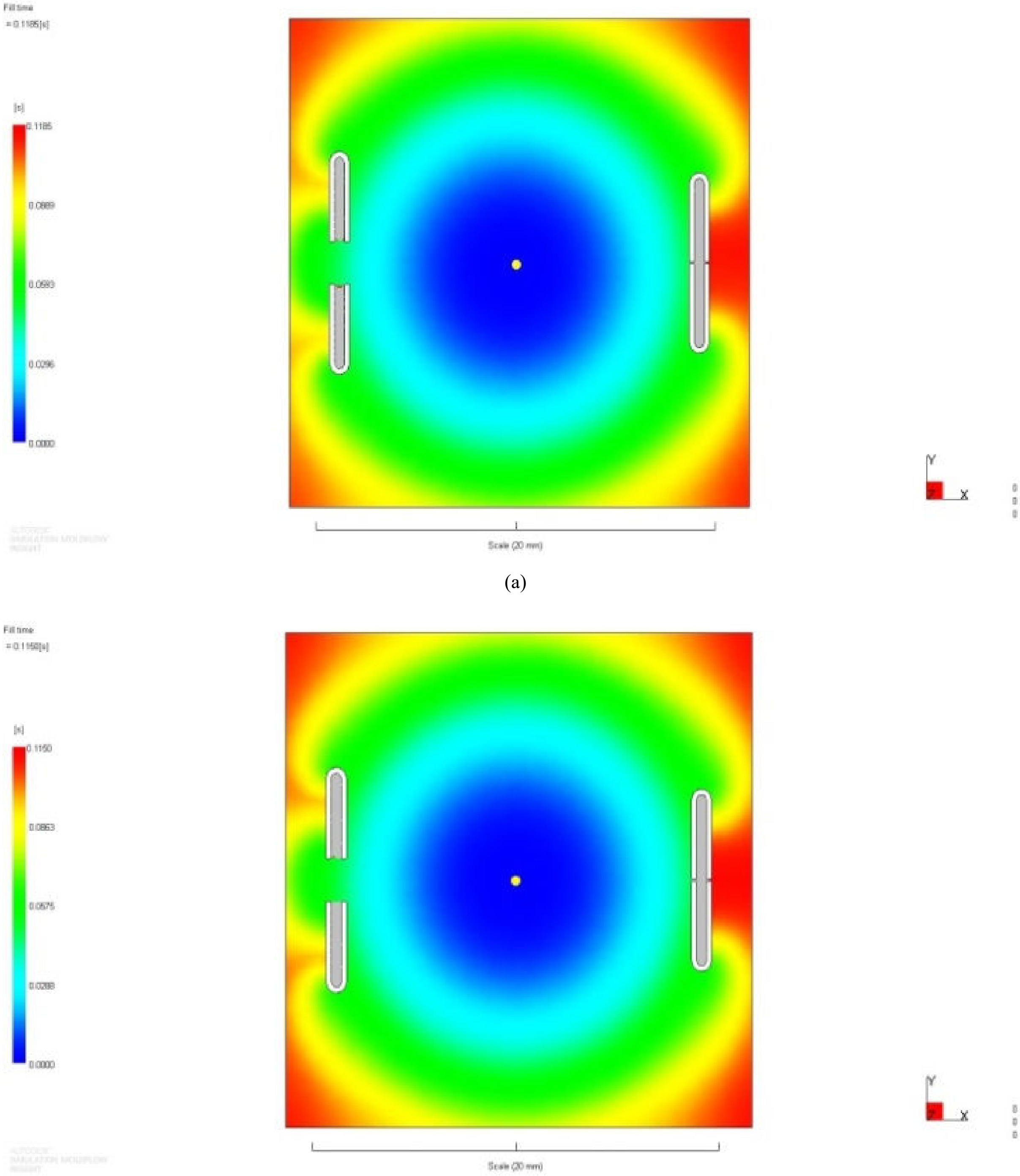
On the other hand, the 3D simulations for R1 and R3 indicate same flow length for both PP and ABS. However, for ABS the T_m was much higher than PP. The achieved flow length proved the accuracy of data obtained from DoE analysis (Fig. 3 (b)) which showed the negligible effect of T_m on the replication of micro cantilevers.

TABLE III
FACTOR SETTINGS RESULTING IN MAXIMUM FLOW

	Material	Simulation settings			
		T_b[˚C]	T_m [˚C]	t_i [s]	D [µm]
R1	PP	270	10	0.1	30
R2			70		120
R3	ABS	270	90	0.1	30
R4					120

TABLE IV
THE RESULTS AS PERCENTAGES OF MAXIMUM FLOW LENGTH

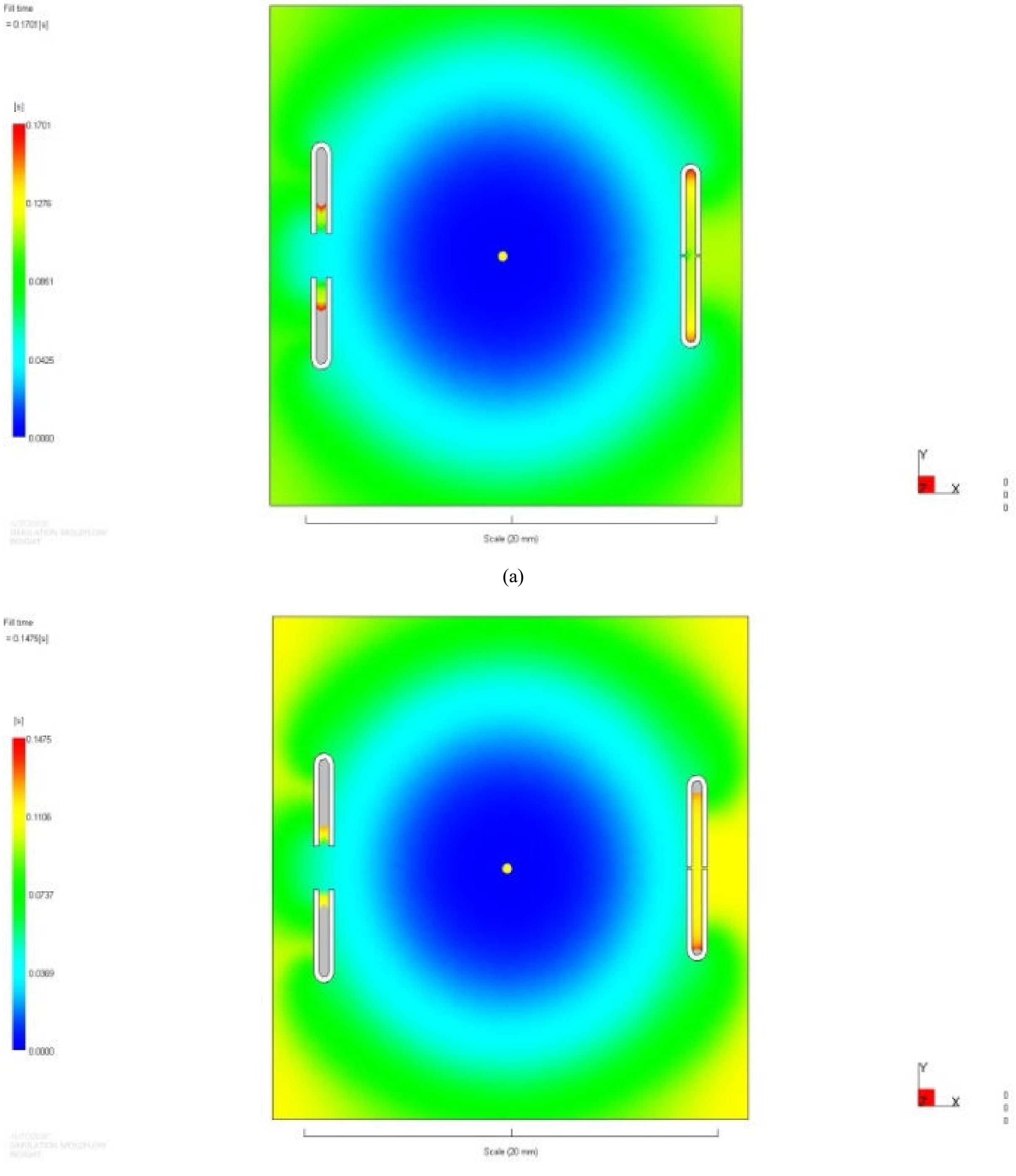
Flow length simulations	Dual-domain simulation filled %	3D simulation filled %
R1	99.70	99.77
R2	99.93	99.873
R3	99.03	99.77
R4	99.91	99.798
Average %	99.64	99.80



(a)

(b)

Fig. 4 Dual-domain maximum flow length for PP and ABS, (a) R1 and (b) R3



(a)

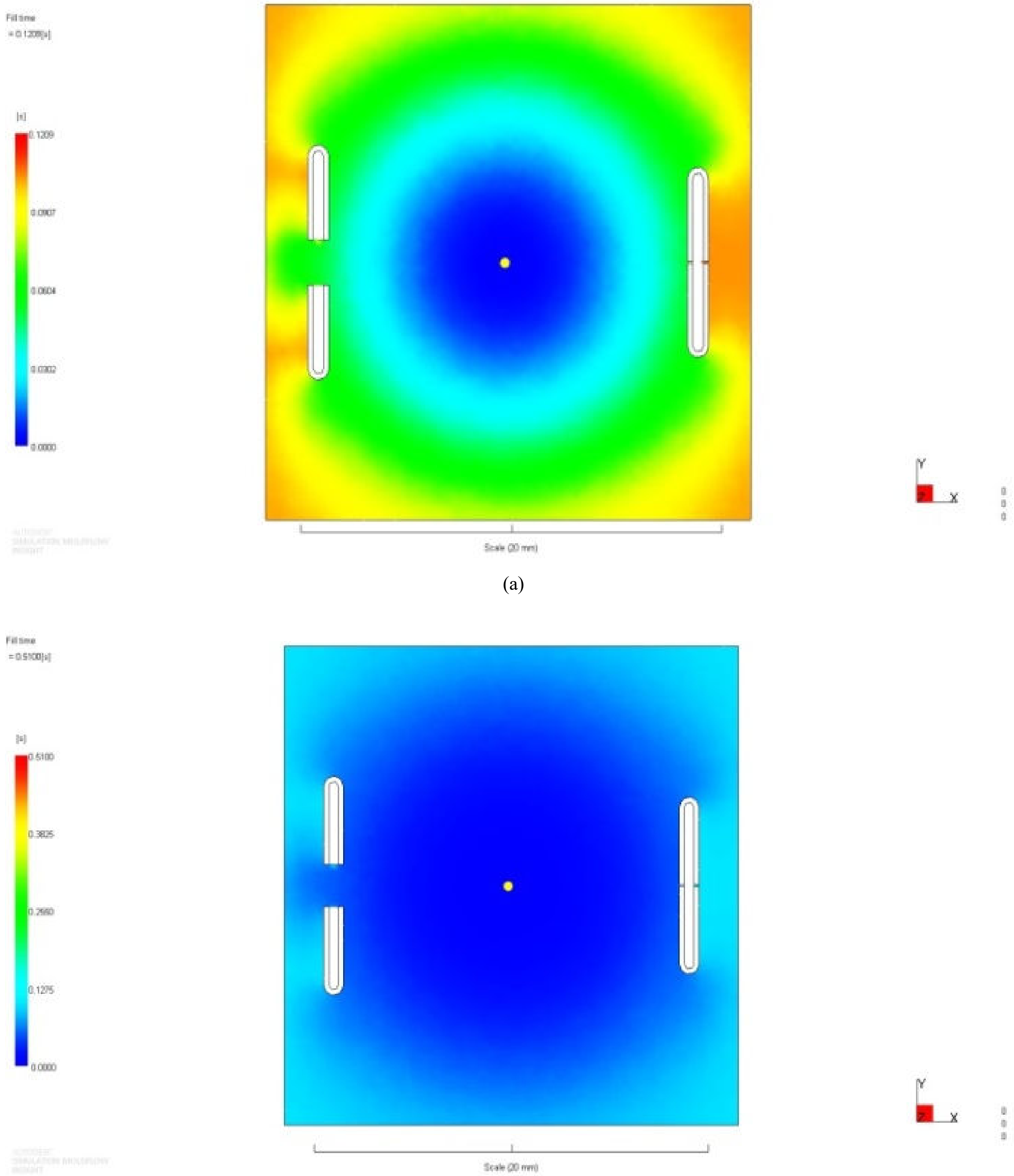
(b)

Fig. 5 Dual-domain maximum flow length for PP and ABS, (a) R2 and (b) R4

For mould inserts including features 120 μm in depth, the simulation runs corresponding maximum flow lengths obtained in the study are R2 and R4. As it was the case with the dual domain results of 30 μm features, the cavity was not completely filled in both simulation runs. However, the melt advance in micro features was significantly higher than those in R1 and R3. As it can be seen in Fig. 5 (a), in the case of PP one of the micro features was completely filled and melt flew into two other cantilevers. When the T_{ff} decreased to 220 ˚C, the melt advance slowed down and finally stopped at T_{ff} 150˚C. For ABS, the filling behaviour was similar to micro cantilevers with 30 μm in depth. Although the range of T_{ff} variation was shorter than PP, the filling percentage was lower. As it was mentioned, the higher viscosity of ABS could be a reason for that.

The closeness of the dual-domain R2 and R4 results suggest that some other factors that are not taken into account in this simulation study affect the flow behaviour and length, and the applied models are less sensitive to T_m. 3D results of R2 and R4 (Figs. 7 (a) and (b)) simulations depicted lower filling percentage in comparison with dual domain results which is assumed to be closer to actual results due to accuracy of mesh applied in this model.

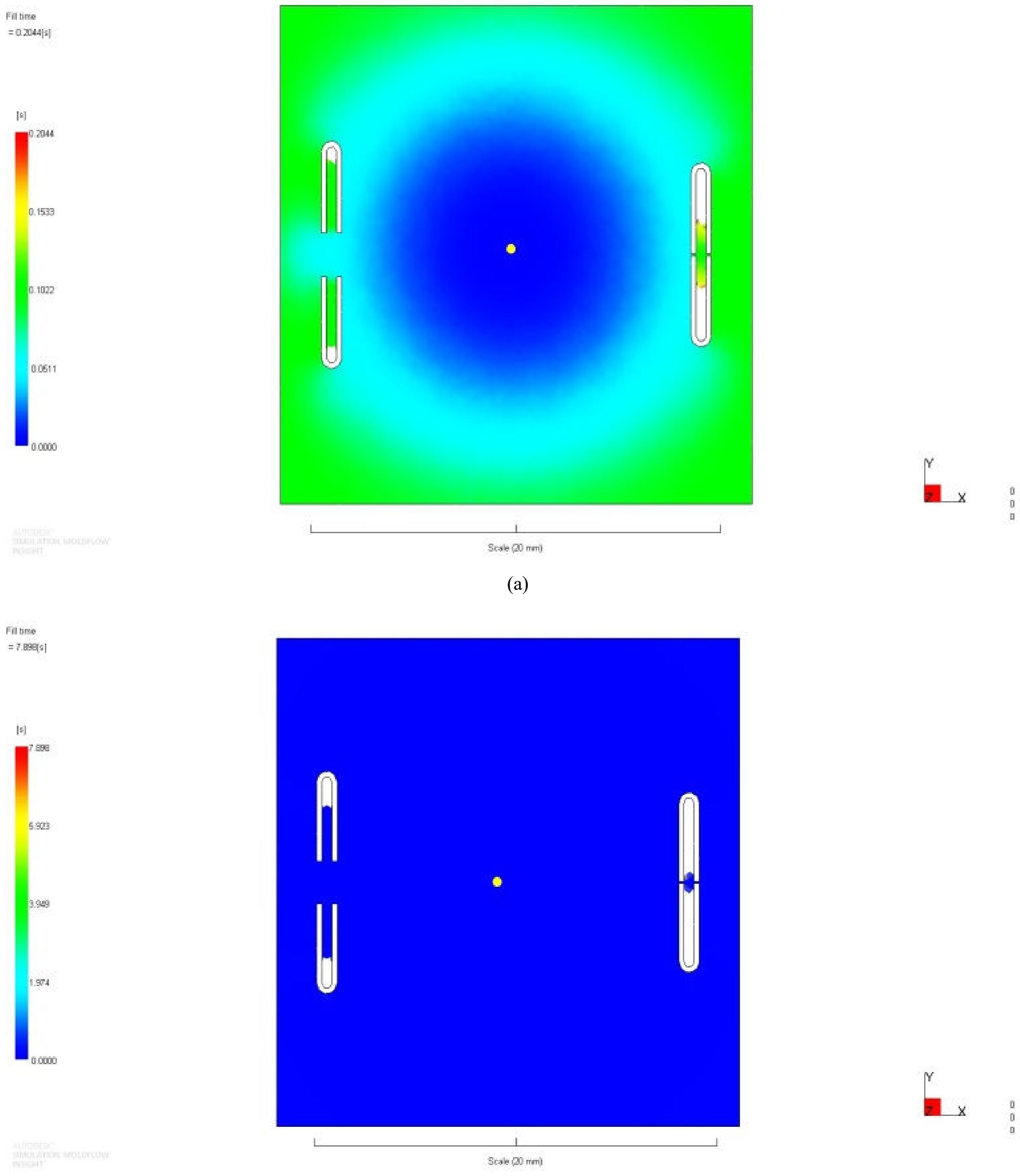
Overall, the average of filling percentage was higher in 3D simulation model for both micro features depth comparing to dual domain model. As it can be seen in Table IV, the average estimation of cavity filling for dual-domain and 3D models are 99.64% and 99.80% , respectively.



(a)

(b)

Fig. 6 3D maximum flow length for PP and ABS, (a) R1 and (b) R3



(a)

(b)

Fig. 7 3D maximum flow length for PP and ABS, (a) R2 and (b) R4

VI. CONCLUSIONS

This work investigates the effects of process and size factors on the replication capability of the micro-injection moulding process within the conventional mould temperature scope. The following conclusions could be drawn from this study.

- T_b and V_i were the key factors affecting the flow length achievable in replicating micro features in PP and ABS.
- T_m does not have any significant effect on the filling behaviour of micro features in case of using polymers such as PP and ABS which are not so sensitive to mould temperature changes.
- An increase of D of micro-cantilevers improves the melt flow because it leads to reduction of the surface-to-volume ratio in micro cavities. However, the melt fill of

micro features does not increase linearly with the increase of cantilevers thickness.

- Although the variations of T_{ff} in response to varying process parameters were much higher for PP in comparison with ABS, these changes in the process parameters did not have any significant effect on the flow lengths achieved.

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