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Optimization of Nozzle Section in Plastic Injection Moulding Process

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ABSTRACT

In this study, the thermal analysis and numeric modelling of flow in nozzle of a real plastic injection machine with injection weight of 300 gram were conducted. The nozzle geometry was changed to optimize flow in nozzle for high-density polyethylene (HDPE) at temperature of 200 °C and injection pressure of 150 MPa. For numeric modelling, the ANSYS Fluent R14 was used. The analysis was made for four different geometries consisting of real system dimension (r-NG) and others design dimensions (NG1, NG2 and NG3). The results of the analysis showed that the most suitable flow was determined in the third (NG3) design. In this geometry, for flow in the nozzle section, rounding was made in the sudden shrinking flow section to give a throat shape and so, the geometry ensuring optimized flow was obtained. As a result, with changing of nozzle geometries of plastic injection machines having different pushing capacities they were used in the industry, the positive results will be able to be obtained.

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INTRODUCTION

Plastics was discovered at the end of the 19th century and developed further, especially after the Second World War. They were begun to be used in the industry and in our daily life with its thousands of varieties [1-3]. For plastic part manufacturing determined according to the physical and chemical characteristics of plastic, various manufacturing techniques have been developed (injection, extrusion, blowing, etc.). Almost 33% of plastic parts are manufactured by using injection moulding technique [4,5]. It is widely used in mechanical construction, automotive components, aerospace and aeronautical industries, and household products. Many studies have been made on manufacturing with injection moulding technique that has an extensive manufacturing capacity [6-9].

This technique enables a low cost and efficiency, fast production cadence, and high dimensional accuracy of complex plastic parts. The quality, geometrical structure, dimension tolerance, surface quality and factors affecting strength of the parts manufactured with the help of injection moulding technique have been the subject of several investigations. The dimensional change (contraction) is one of the main factors that has an effect on the quality of moulded product. It is tried to be put under control depending on the injection parameters (such as injection temperature, injection pressure, cooling period, additive material, kind of plastic raw material, crystallization rate of plastic, shape and wall thicknesses of moulded part, wall thickness change, number of inputs and distance between inputs, type of filling of mould space) [10,11]. In view of this, mould designers are using computer-based programs to optimize the injection moulding process. The factors affecting the product quality during the process have been tested and verified by many researchers in their theoretical and experimental studies [12-14] and by using various ready package programs [15,16]. Recently, Kuo and Su [17] optimized the plastic injection process with statistical methods in an experimental study by using the Taguchi technique. Shie [18] determined optimal parameters in the injection moulding process by using the artificial neural networks method. Shi et al. [19] developed a new model to optimize the plastic injection process by using the genetic algorithm method. Lee and Lin [20] studied the runner and gating system parameters for a multi-cavity injection mould by using artificial neural networks with finite elements method. Mathivanan and Parthasarathy [21] developed an injection moulding model with mathematical and statistical techniques, by using the surface reaction methodology. Das Neogi [22] forecasted the analysing outputs of the change in dependent variables linked on the independent variables in the plastic injection process, by using the linear regression model. Zhang and Alexander [23] diagnosed the difficulties in the plastic injection process by observing the pressure signals in mould cavitation via the pressure cavity pressure signals.

The design of an injection moulded part and machining is difficult, especially the design of the feeding system, the latter which includes the sprue, the runners and the gates are more difficult. Although many principles and theories have been developed in the plastic injection modelling over past decades, there is no assurance that quality machining and a corresponding quality moulding can be manufactured. Traditionally, design of an injection moulded part and its machining is accomplished by accumulated experience. However, the ever-increasing customer demands for quality and low cost have led to the requirement of best possible quality [24].

Most defective and damaged plastic moulds are caused by incorrect design of the feeding system. Thus, most effective injection nozzle should be developed to remedy such design faults and allow plastic moulders to make better quality plastic parts with minimum investment and higher output. For this reason, Lau and Tse [25] talked about the anti-backflow, anti-leakage and pressure compensated (ABLPC) injection nozzle. They reported that the ABLPC nozzle showed a better performance compared to a standard nozzle. Yilmaz and Kirkkopru [26] modelled flow in extrusion of profiles having complicated cross-section. For analysis, they used the Bird-Carreau viscosity model in Polyflow program. Thus, they developed a method to solve the problem of unbalanced extrusion of polymer melt from mould. They determined that speed distribution at the mould outlet cross-section was consistent. Dumitrescu et al. [27] observed the flow behaviour of polymers passing from the nozzle section of 150 tones injection machine, during the plastic injection process. By using optical fibber probes with infrared spectrometer method, they optimized the polymer flow for different process features and materials. Ozdemir et al. [28] modelled the extrusion process during compounding of a polyamide material at a double-screw extruder machine, and compared the obtained results with actual results. They made the numeric modelling by using the Polyflow and Fluent software. They improved the extruder head geometrically to eliminate irregularities in flow. Sardarian et al. [29] simulated filling stage for low pressure injection moulding of aluminium by finite element method. They showed that simulation was found to correctly describe trends such as; an increase in the pressure required to fill moulds as temperature decrease. Zhuang et al. [30] developed a 3D thermal model to simulate viscoelastic polymer melt packing process in injection moulding. They showed that with an increase in melt temperature, the precise values of the first normal stress difference increased slightly, while the density decreased by stages. The high holding pressure enhanced significantly the first normal stress difference and density. Also, they reported that the present 3D thermal model was an effective tool for simulating real-world viscoelastic polymer melt packing processes. Zhang et al. [31] proposed an approach that could use the predicted errors when examining the micro-properties of typical microfluidic chips with micro injection moulding. They concluded that heat transfer coefficient showed a significant impact on filling of micro-properties. Wittemann et al. [32] provides a novel simulation method for reactive injection moulding that describes fibber-induced anisotropic flow behaviour with a fourth order viscosity tensor. Theirs study showed that cavity pressure and fibber orientations confirmed by experimental data.

Although, within the knowledge of authors, there is no study in literature that was determined about thermal and dynamic behaviours of flow in nozzle section of a plastic injection. The studies made on plastic injection process generally remain within the limits of inside of mould. If the melt material accumulated in the front of the nozzle section during the plastic injection process is propelled with pressure from side of screw, it demonstrates a flow in the nozzle section before entering in the mould. Although experimental modelling of flow in the nozzle section is technically very difficult, numeric modelling of flow in this section may be easier and give more reliable results. For removing the deficiency on this subject in the literature, using of optimization in practice will make a great contribution in the plastic injection process and in the literature.

MATERIAL AND METHODS

In this study, the referenced nozzle geometry is that of the nozzle used in the Ekin 160-B coded injection machine of 160 tones shown in Fig. 1, manufactured by the Ekin Machine Inc. Its technical features are given in Table 1. Also, this machine was used in the Industrial Thesis (SAN-TEZ) Program of the Ministry of Science, Industry and Technology in Turkey. In the study, flow in the nozzle section is optimized by using the Simple algorithm in ANSYS Fluent R14 software. The high-density polyethylene (HDPE), mostly used in manufacturing of plastic products, are used in the study and its properties are given Table 2, at pressure of 150 MPa and temperature of 200 °C. To optimize flow in the nozzle, the most appropriate process characteristics are given in Table 3. Thus, the geometrical changes are made on the real nozzle geometry (r-NG). And then, three different geometries (NG1, NG2 and NG3) are obtained for the flow optimization. Finally, the obtained results were evaluated and compared with each other.

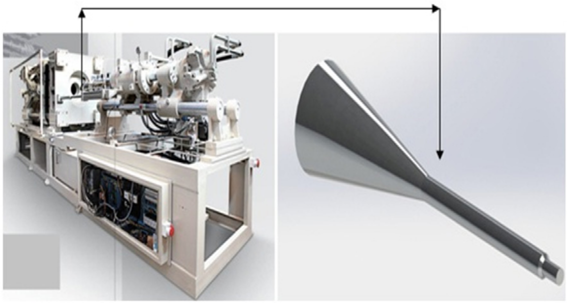

Figure 1. Ekin 160 – B plastic injection machine and its injection nozzle

In this study, some studies [3,27-33] are considered as a reference for solving of mathematical equations. For the finite volumes method, the balance equations such as the continuity, momentum, energy and Bird-Carreau viscosity model are solved numerically in the ANSYS Fluent R14 software, as given the following:

Continuity equation

$$\nabla \cdot u = 0 \tag{1}$$

Momentum equation

$$\rho \frac{\partial u}{\partial t} - \nabla \cdot \eta \left(\nabla u + \left(\nabla u \right)^T \right) + \rho u \cdot \nabla u + \nabla P = 0 \tag{2}$$

Energy equation

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial P}{\partial t} + k \nabla^2 T + \eta \Phi \tag{3}$$

Bird-Carreau viscosity model

$$\eta = \eta_\infty + \left(\eta_0 - \eta_\infty \right) \left[1 + \left(\lambda \dot{\gamma} \right)^2 \right]^{\frac{(n-1)}{2}} \tag{4}$$

where $\dot{\gamma}$ denotes a scalar quantity and can be calculated using components of the strain rate tensor, as follow:

$$\dot{\gamma} = \sqrt{I_2/2} \tag{5}$$

where I_2 is the second invariant of the strain rate tensor as

$$I_2 = \sum_i \sum_j \dot{\gamma}_{ij} \dot{\gamma}_{ji} = \dot{\gamma}_{xx}^2 + \dot{\gamma}_{xy}^2 + \dot{\gamma}_{xz}^2 + \dot{\gamma}_{yx}^2 + \dot{\gamma}_{yy}^2 + \dot{\gamma}_{yz}^2 + \dot{\gamma}_{zx}^2 + \dot{\gamma}_{zy}^2 + \dot{\gamma}_{zz}^2 \tag{6}$$

The Bird-Carreau viscosity model was used in solving of viscosity equation because of the fact that gives more accurate and reliable result in modelling of polymer flows [3,28]. For discretization of these equations, the Simple Algorithm is used for the ANSYS Fluent R14 software.

Table 1. Technical properties of the Ekin 160 – B plastic injection machine

Properties	Value
Screw diameter (mm)	45
Screw L/D ratio	21
Shot size (cm^3)	332
Injection weight (g)	300
Injection rate (g/s)	118
Plasticizing capacity (g/s)	22
Injection pressure (MPa)	150
Screw speed (rpm)	0-230
Screw stroke (mm)	210
Clamping force (kN)	1600
Toggle stroke (mm)	385
Space between tie bars (mm)	410x410
Max mould height (mm)	450
Min mould height (mm)	100
Ejector stroke (mm)	120
Ejector force (kN)	35
Ejector number (PC)	1
Heater power (kW)	8.5
Machine dimensions (m)	5.4 x1.2 x1.8
Machine weight (T)	4

Table 2. Properties of high-density polyethylene (HDPE) at 200 °C

Properties	Value
Zero shear viscosity, μ_o (Pa.s)	5255
Infinity shear viscosity, μ_∞ (Pa.s)	0
Material density, ρ (kg/m3)	951
Natural time, λ(s)	0.96
Power-law index, n	0.496
Material melting temperature, T_{melt} (°C)	176 (440 K)

Table 3. Properties of the analysis process

Properties	Value
Inlet pressure, Pin (MPa)	150
Inlet temperature, Tin (°C)	200 (473 K)
Nozzle material	Steel
Nozzle wall	Adiabatic wall

RESULTS AND DISCUSSION

The purpose of this study is to make the optimization of nozzle section in plastic injection machine. In this process, cavitation that occur as a result of high pressure fluctuations cause sudden change in speed and temperature of injection process and thus phase of material changes. The change of phase causes porosity and gives da-

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mage to the material structure in the mould. To increase the moulded material quality and improve the process, the nozzle geometry should be enhanced. In this study, flow in nozzle is optimized by the ANSYS Fluent R14 software considering to the features of plastic injection machine, properties of high-density polyethylene (HDPE) and conditions of injection process given in Tables 1-3 on the basis of original/real nozzle geometry of which solid model picture is given in Fig. 1. The original/real nozzle geometry (r-NG) and the developed design geometries (NG1, NG2 and NG3) are illustrated in Fig. 2.

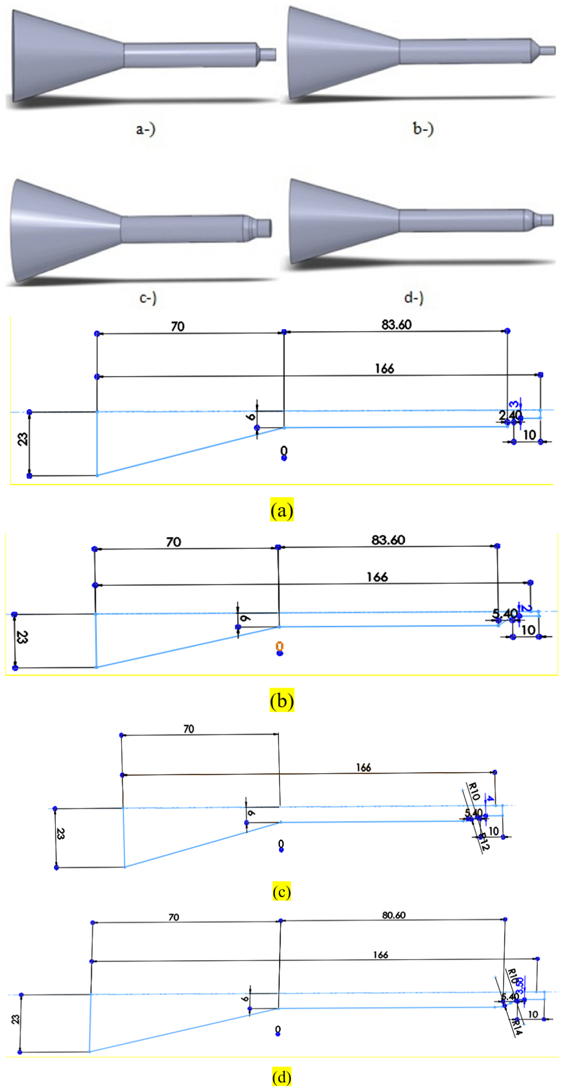
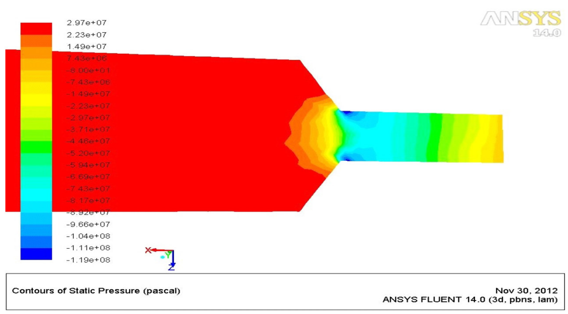
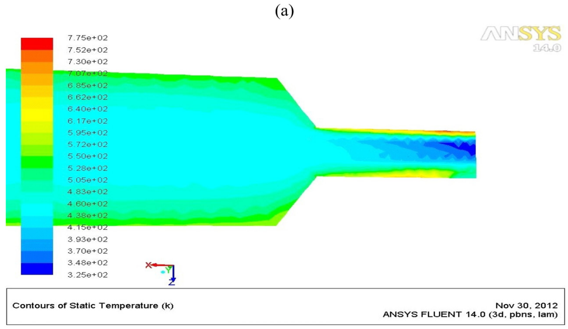


Figure 2. The solid modelling and measurement of (a) the real nozzle geometry (r-NG), (b) the first (NG1), (c) the second (NG2) and (d) the third (NG3) nozzle geometry designs.

The pressure and temperature contour distributions for the real nozzle geometry (r-NG) with its boundary conditions (see Fig. 2(a)) are shown in Fig. 3. As can be seen in Fig. 3(a), vacuum occurs in the sudden shrinking region of nozzle and pressure drops in this section. Then, when the fluid moves away from the sudden shrinking section, static pressure of the fluid (HDPE) increases again. And the fluid at exit of nozzle leaves the nozzle with about pressure of 7 MPa. From Fig. 3(b), in the sudden shrinking section where temperature increase occurs because of the viscosity of melting plastic fluid at nozzle walls, the temperature of plastic fluid in axis and throughout the nozzle falls below the melting temperature of the plastic material. Thus material solidification occurs. The temperature of the HDPE in the solidification section decreases to 52 °C (325 K). In the r-NG, the solidification process at the end of the nozzle occurs while the fluid passes from the nozzle section, as seen in Fig. 3(b) for blue colour sections. For optimizing of the r-NG, the second design (NG1) is obtained by extending the length of sudden narrowing section from 2.40 mm to 5.40 mm and reducing the exit diameter of the sudden narrowing section from 3 mm to 2 mm on the real nozzle geometry, as illustrated in Fig. 2(b).



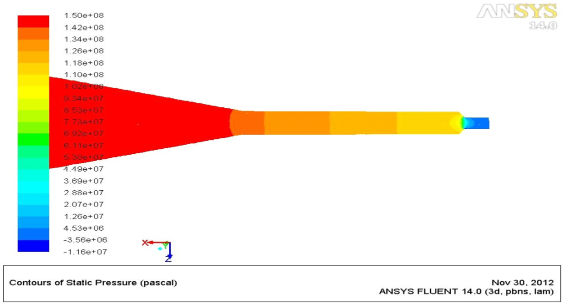
(a)



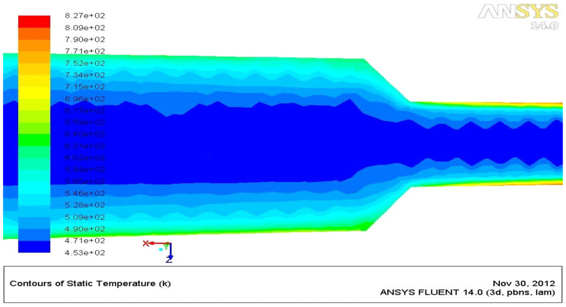
(b)

Figure 3. The distributions of pressure (a) and temperature (b) in nozzle section for the r-NG

The results of the analysis performed for the NG1 are presented in Fig. 4. In Fig. 4(a) for the pressure distribution, it is seen that vacuum occurs in the sudden shrinking section. This causes cavitation. As can be seen in Fig. 4(b), the temperature in middle of cross-section throughout the nozzle did not fall below 180 °C (453 K) while the temperature distribution throughout nozzle walls increases to 554 °C (827 K) because of the viscous dissipation. With a more stable increase in fluid velocity, there is no solidification zone in the flow of the HDPE material for the NG1 due to no sudden drop in temperature. However, the sections with temperature of 180 °C (453 K) tend to be close to solidification temperature. This is not a desirable result.



(a)

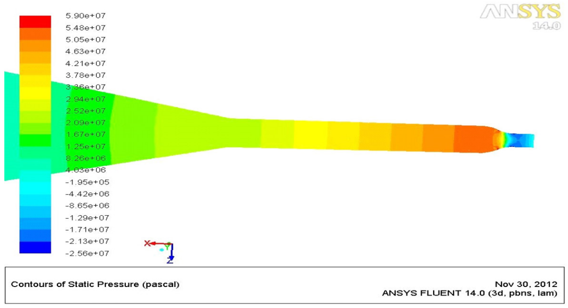


(b)

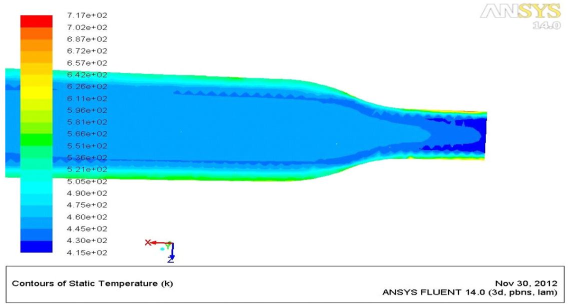
Figure 4. The distributions of pressure (a) and temperature (b) in nozzle section for the NG1.

To find a design in which the lowest temperature in the nozzle section will be higher than 440 K, design of the NG1 is changed. Thus, the second design (NG2) is considered as illustrated in Fig. 2(c). For more stable flow at nozzle, by rounding sudden shrinking section of 10 mm and increasing the exit diameter of the sudden shrinking section from 2 mm to 4 mm in the NG1, the NG2 geometry is obtained. Fig. 5 shows the results of analysis for the NG2. In Fig. 5(a), it is observed that cavitation occurs at the tip of nozzle because of sudden pressure fluctuations in the pressure distribution counters in the nozzle section. With sudden increase in fluid velocity, phase change in the HDPE material is occurred. Regard in Fig. 5 (b), it can be seen that the temperature of fluid in the middle cross-section decreases to 142 °C (415 K) while the temperature at the side walls of nozzle increases to 444 °C (717 K), because of the viscous heating in flow of the nozzle section. In here the solidification formation is observed as the temperature of fluid in the middle cross-section of nozzle tip fell below the melting temperature of 167 °C (440 K). Because of solidification condition, the nozzle in the NG2 becomes unusable. For this reason, the third design (NG3) is passed, as illustrated in Fig. 2(d).

In the NG3, the nozzle outlet diameter is conducted as 3.50 mm, and nozzle outlet is rounded to diameter of 14. The results of analysis for the NG3 are shown in Fig. 6. For the pressure distribution counters, it can be seen from Fig. 6(a) that vacuum occurs in the sudden shrinking section of nozzle tip. During flow of the HDPE material in the nozzle section, the temperature in the middle cross-section is higher value compared to nozzle section in the original (r-NG)



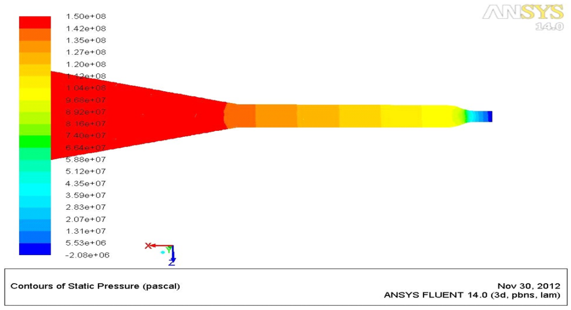
(a)



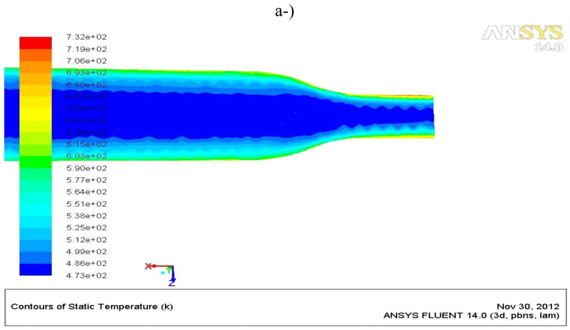
(b)

Figure 5. The distributions of pressure (a) and temperature (b) in nozzle section for the NG2.

and the others (NG1 and NG2) designs, while the temperature distribution increases to 459 °C (732 K) at wall sections of nozzle tip (see Fig. 6(b)). In the NG3, the temperature in the middle cross-section of nozzle decreases to 200 °C (473 K).



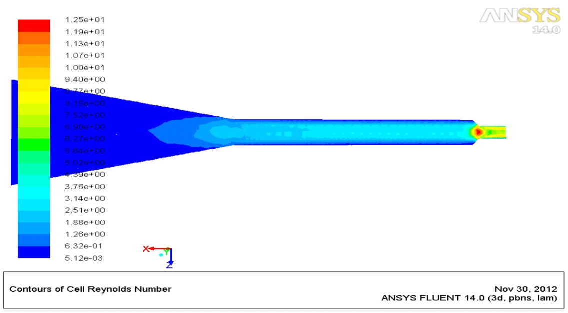
a-)



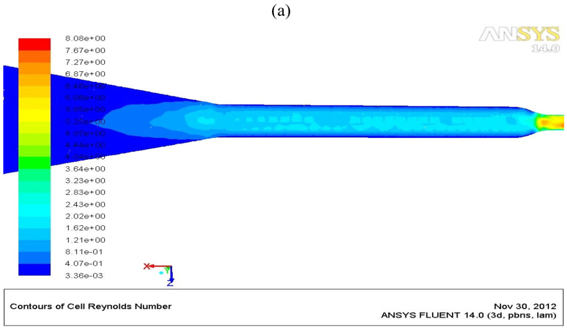
(b)

Figure 6. The distributions of pressure (a) and temperature (b) in nozzle section for the NG3.

In the optimization work, due to solidification in nozzle section of the original/real (r-NG) and second (NG2) designs, these type nozzles are not recommended to use in the plastic injection process. As a result, the first (NG1) and third (NG3) designs can be used in the plastic injection process. For the NG1 and the NG3 designs, the more stable flow in the nozzle section can also be investigated. The Reynolds number distribution for each design is shown in Fig. 7. Note that the temperature at nozzle tip of the NG3 decreases to 200 °C (473 K) while that of the NG1 decreases to 184 °C (457 K). In addition, it can be understood that the maximum Reynolds number in flow of nozzle section in the NG1 increase to 12.5 while that in the NG3 increases to 8.08, as shown in Figs. 7(a) and 7(b), respectively.



(a)



(b)

Figure 7. The distributions of the Reynolds number in nozzle section for the NG1 and NG3 nozzle geometries.

Optimizing criterion of flow is summarized that: (i) Reynolds number distribution in the flow section must be lower (namely, laminar flow), (ii) the lowest value of temperature at nozzle exit must be higher. According to the determined criterion, the nozzle geometry in the NG3 is optimum nozzle geometry.

CONCLUSION

In this study, the nozzle section of the Ekin 160-B coded plastic injection machine with 160 tones is numerically investigated for the thermal analysis of the HDPE material flow. First, the original/real nozzle geometry (r-NG) is analysed by ANSYS Fluent R14 software. The others nozzle geometries (NG1, NG2 and NG3) are then optimized by changing the r-NG. According to the analyses, the r-NG and NG2 are not convenient as there will be solidification in the flow of nozzle section in plastic injection machine. For the NG1 and NG3, no solidification occurs in flow of nozzle section of the plastic material. Additionally, in the NG3 the Reynolds number change is smaller value while the temperature in nozzle output is 200 °C (473 K). However, in the NG1, the Reynolds number change is higher value as the temperature of HDPE material is 184 °C (457 K). The temperature of flow in nozzle output should not be near to melting temperature (167 °C = 440 K) of HDPE material. This is the most ideal situation. In other words, the nozzle geometry in the NG3 is the most optimum geometry. Porosity formation during flow will be very less and thus the material quality in mould will be the highest. Rounding of narrowing cross-section geometry in the sudden narrowing flow sections during the plastic injection process prevents porosities that occur in the flow and ensures the flow to be more perfect. Extensive usage of nozzle designs in the industrial applications to be made by considering the nozzle geometry established as a result of geometrical improvements will create an important economic advantage for the plastic injection process that is one of the widely used manufacturing methods. In future studies to be realized by taking this study as a basis, the improvements will be made in the nozzle section of different capacity machines for plastic injection process, very important advantage in cost of plastic injection process will be obtained and besides, and optimization of this process will be able to be realized.

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NOMENCLATURE

C_p	specific heat capacity (kJ/kgK)
I	invariant of strain rate tensor
k	heat transfer coefficient (W/mK)
L	length (m)
n	flow behaviour exponent /power-law (-)
P	pressure (Pa)
Re	Reynold number (-)
t	time (s)
T	temperature (°C or K)
u	velocity (m/s)

Greek symbols

γ	scalar quantity
ρ	fluid density (kg/m3)

η_0	zero stress viscosity (kg/ms)
η_∞	infinity shear stress viscosity (kg/ms)
λ	time constant (s)
∇	nabla

Subscripts

in	input
out	output
x, y, z	coordinate

Abbreviations

ABLPC	anti-backflow, anti-leakage and pressure compensated
D	dimension
HDPE	high-density polyethylene
NG	nozzle geometry

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