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Automated Mould Cooling Technique for Improving Product Quality in an Injection Moulding System

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ABSTRACT

The design and simulation of an Automatic water circulation process for injection mould cooling using an embedded system for temperature control in a plastic industry is the focus of this work. Injection mould cooling is one of the most important processes in the plastic manufacturing industry. More than one-third of all plastic products are injection moulded and mould cooling is essential in the production process. The optimum temperature or ejection temperature (T_{EJECT}*) of the material to be moulded is preset in the microcontroller. This temperature depends on the melting temperature of the plastic materials being used because different plastic materials have different melting temperatures. The system senses the temperature from the source particularly high temperature source via a heat sensor such as thermocouple. The sensor output signal is conditioned and fed to the microcontroller (here, AT89C52 microcontroller is used) which drives a relay through a switching unit for switching the system to ON-OFF position. The work also describes the system control action incorporated in the hardware for obtaining the desired cooling process. The design analysis software- matlab and excel, are used for simulation in addition to Embedded C and Proteus professional. The results obtained from the process shows that it is very viable as it saves substantial consumption of power, achieves reduction in quantity of water usage in cooling and also reduces material wastage. It is more economical than the manual mould cooling method by removal of drudgery and maintaining uniform cooling process.*

Key words: Injection mould, microcontroller, manufacturing, temperature, simulation

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INTRODUCTION

Automation of mould cooling is the continuous movement of water in a circuit or loop, which is maintained chiefly by the action of some assemblage of components to keep the constant supply of water to perform the required function intended. The Automation of the cooling is required to optimise the cooling process, thereby improving product quality and also, eliminating some anomalies caused using manually operated cooling system.

This project is aimed at circulating water for injection mould cooling in the plastic parts production. Plastic is a material consisting of a wide range of synthetic or semi-synthetic organics that are malleable. It can be moulded into solid objects of diverse shapes. Plastics are typically organic polymers of high molecular mass that often contain other substances. They are usually synthetic, most commonly derived from petrochemicals, but many are partially natural [1]. Due to their relatively low cost, ease of manufacture, versatility, and imperviousness to water, plastics are used in an enormous and expanding range of products; from paper clips to spaceships, automobiles (up to 20% plastic), furniture and toys [2]. A shift from metal to plastic use in medical sector due to inexpensiveness, ease of production, ease of cleaning, and sterilization of plastic materials, which can be injection moulded, makes it gain more acceptability with reduced sterilization requirements is the case presently.

Injection moulding has been the most popular method for making plastic products due to high efficiency and manufacturability. There has been a tremendous increase in the demand for injection moulded products over the past several years. Initially, the process concentrated on producing high volume parts with low to moderate quality requirements. In recent time, the market has expanded to include precision moulded parts requiring high quality cooling control using sensors such as thermocouple. There is need for improving the process to increase productivity, reduce the cycle time in injection moulding. In order to achieve the processing parameters, a new generation designers require more powerful software to model injection mould cooling process by manipulating parameters to reduce cycle time. The injection moulding is divided into five separate steps: plastification, injection, holding, cooling, and finally ejection. The time used from the injection of the melt into the cavity to the ejection of the finished part is the most significant parameter in the calculation of the cost of manufacturing a plastic part. This is called the cycle time [3]. Among these stages, cooling stage is very important one because it mainly affects the productivity and moulding quality. Normally, 70% - 80% of the moulding cycle is taken up by cooling [4]. Appropriate temperature and flow rate of coolant reduce the cooling time and increase the productivity of the injection moulded parts. On the other hand, an efficient cooling system which achieves a uniform temperature distribution can minimize residual stresses and undesired defectssuch as hotspots, sink marks, differential shrinkage, thermal residual stress, and warpage, and maintain dimensional accuracy and stabilitythat influence the quality of moulded part [5].

METHOD

Automatic cooling system apparatus is employed here to keep the temperature of injection mould from exceeding limits imposed by needs of safety and efficiency as explained by Newton's Law of Cooling, which states that, “the rate of change of the temperature of an object is proportional to the difference between its own temperature and the ambient temperature [6]. The coolant used is water which is considered the most efficient means of removing unwanted heat. A cooling tower is the most important piece of the equipment of which its primary purpose is to remove heat by means of a draft fan while minimizing water usage.

Mould cooling is a function of three factors, namely:

- ✓ Coolant circulating rate.
- ✓ Coolant temperature.
- ✓ Efficiency of the overall heat transfer system (temperature optimization).

Mould cooling analysis is modeled and the resulting equationis resolved, using matlab and excel software to determine the optimum temperature. Embedded C software in conjunction with Proteus professional software is used to simulate the electrical control process of the injection mould cooling, with reference to the optimum temperature and volumetric flow rate at a reduced cycle time for the best quality and economy.

MATHEMATICAL MODEL

The models are derived froma set of mathematical equations describing the physical process behavior of a particular case under investigation, as utilized below. Based on the principle of conservation of energy, in a process analysis with accumulation of internal energy, the heat flow that is supplied to the mould and the heat flow that is removed from the mould should be in thermal equilibrium, in every single moment, with the heat accumulated in the structure of the mould (Zeroth’s law of thermodynamic): to define the energy swing, is an established equilibrium between the heat powers that are introduced in the mould, the heat power accumulated in every single moment in their interior and the heat powers removed from the mould, being positive or negative regarding those that respectively increase or diminish their internal energy [7], (Newton's Law of Cooling) [8].

Therefore;

$$Q_{pl} - Q_{AMB} - Q_{coolant} = Q_{Accum} \qquad (1)$$

Where

Q_{pl} = Heat flow supplied by the polymer (polypropylene)

Q_{AMB} = Heat flow lost to the environment.

$Q_{coolant}$ = Heat flow transferred for the coolant (water).

Q_{Accum} = Accumulation energy in the mould material per unit time.

Assumptions:

Minimal or no heat loss to the surrounding

Therefore, Eqn (3.1) becomes

$$Q_{pl} - Q_{coolant} = Q_{Accum} \qquad (2)$$

But

The energy accumulated in the mould is given as

$$Q_{Accum} = \frac{\rho_m C_m \delta T_m}{\delta t} \qquad (3)$$

$$Q_{coolant} = \frac{M_c C_c (T_F - T_{AMB})}{t} \qquad (4)$$

Writing equation (3.4) in terms of volumetric flow rate, we have;

$$Q_{coolant} = q_c C_c (T_F - T_{AMB}) \qquad (5)$$

Where, $q_c = \frac{M}{\rho * t}$

Where; q_c is the volumetric flow rate of the coolant in m^3/sec,is Mass in Kg, is density in Kg/m^3 and is time in second.

$$Q_{pl} = \frac{\rho_p C_p L_p (T_{meit} - T_{eject})}{t_{cycle}} \qquad (6)$$

Substituting equations 3, 5 and 6 into equation 2, we have;

$$\frac{\rho_m C_m \delta T_m}{\delta t} = \frac{\rho_p C_p L_P (T_{melt} - T_{eject})}{t_{cycle}} - q_c C_C (T_F - T_{AMB}) \qquad (7)$$

Since cycle time (t_{cycle}) is equal to cooling time, t_{cycle}becomes hence equation (7) becomes;

$$\frac{\rho_m C_m \delta T_m}{\delta t} = \frac{\rho_p C_p L_P (T_{melt} - T_{eject})}{t} - q_c C_C (T_F - T_{AMB}) \qquad (8)$$

Assuming that the temperature of the plastic at ejection temperature ($T_{ejection}$) is equal, and taking to be the maximum temperature (T_F) acquired by the coolant. So, $T_{eject} = T_{F,}$ hence equation 3.8 becomes;

$$\frac{\rho_m C_m \delta T_m}{\delta t} = \frac{\rho_p C_p L_P (T_{melt} - T_{eject})}{t} - q_c C_C (T_{eject} - T_{AMB}) \qquad (9)$$

$$\frac{\delta T_m}{\delta t} = \frac{1}{\rho_m C_m} \{ \frac{\rho_p C_p L_P (T_{melt} - T_{eject})}{t} - q_c C_C (T_{eject} - T_{AMB}) \} \qquad (10)$$

Expanding eqn 3.10, we have;

$$\frac{\delta T_m}{\delta t} = \frac{1}{\rho_m C_m} \{ \frac{\rho_p C_p L_P T_{melt}}{t} - \frac{\rho_p C_p L_P T_{eject}}{t} - q_c C_C T_{eject} + q_c C_C T_{AMB} \} \qquad (11)$$

Rearranging eqn 3.11, we have;

$$\frac{\delta T_m}{\delta t} = \frac{1}{\rho_m C_m} \{ \frac{\rho_p C_p L_P T_{melt}}{t} + q_c C_C T_{AMB} - T_{eject} (\frac{\rho_p C_p L_P}{t} + q_c C_C) \} \qquad (12)$$

Taking the sample of half the plastic part thickness (P_l) to be; 1mm or 0.001m
Ambient temperature of the coolant (T_{AMB}) to be; 20^0C
Volumetric flow rate of the coolant (q_c) in m^3/sec is to be determined
Therefore, substituting the values in tables 3.1, 3.2, 3.3, P_l and T_{amb} into eqn 3.12 above and resolved mathematically, we have;

$$\frac{\delta T_m}{\delta t} = 0.1557 t^{-1} + 0.3048 q_c - T_{eject} (0.00035 t^{-1} + 0.001 q_c) \qquad (13)$$

To find optimum value, the first derivative of the function ($\frac{\delta T_m}{\delta t}$) must be equal to zero, hence $\frac{\delta T_m}{\delta t}$ = 0 for optimum value of temperature.

Therefore, equation 3.13 becomes;

$$T_{eject} = \frac{0.1557 + 0.3048 q_c t}{0.00035 + 0.001 q_c t} \qquad (14)$$

Where Teject = optimum temperature or the control temperature required
q_c= the volumetric flow rate in m^3/sec
t = the cycle time (seconds), in this project is the time between the injection of molten plastic to the time of ejection of solidified plastic part, taking to be 15seconds.

RESULT

The final equation for the optimum temperature (T_{eject}) resulting from the mathematical modeling of the injection mould cooling system is analysed using matlab software and the value of optimum temperature (T_{eject}) and the corresponding value of coolant volumetric flow rate (q_c) are obtained for a constant cycle time (t_{cycle}) and half the plastic thickness (P_l). The result of the optimum temperature forms the control parameter for the electrical stimulation of the control process. The modeling and simulation of this work solves the problems of rigidity associated with the manual mode of injection mould cooling as this work makes the variables of cooling parameters flexible for the operators to accomplish effective cooling with ease. The result of different coolant flow rate and the corresponding values of ejection temperature when the half plastic thickness, cycle time and ambient coolant temperature are kept constant, using matlab and excel software for the analysis is shown in the table 1 below whereas the result of ejection temperature against the volumetric coolant flow rate is shown in fig. 1 and fig. 2.

Table -1 Coolant flow rate and Ejection temperature

S/N	Coolant Flow Rate (q_c) in m^3/sec	Optimum Temperature (T_{eject}) in 0^0	S/N	Coolant Flow Rate (q_c) in m^3/sec	Optimum Temperature (T_{eject}) in 0^0	S/N	Coolant Flow Rate (q_c) in m^3/sec	Optimum Temperature (T_{eject}) in 0^0
1	0	170	8	0.35	45	15	0.70	41.20
2	0.05	79.32	9	0.40	44	16	0.75	40.92
3	0.10	62	10	0.45	43	17	0.80	40.67
4	0.15	54	11	0.50	42	18	0.85	40.46
5	0.20	51	12	0.55	42	19	0.90	40.26
6	0.25	48	13	0.60	41.89	20	0.95	40.09
7	0.30	46	14	0.65	41.52	21	1.0	39.93

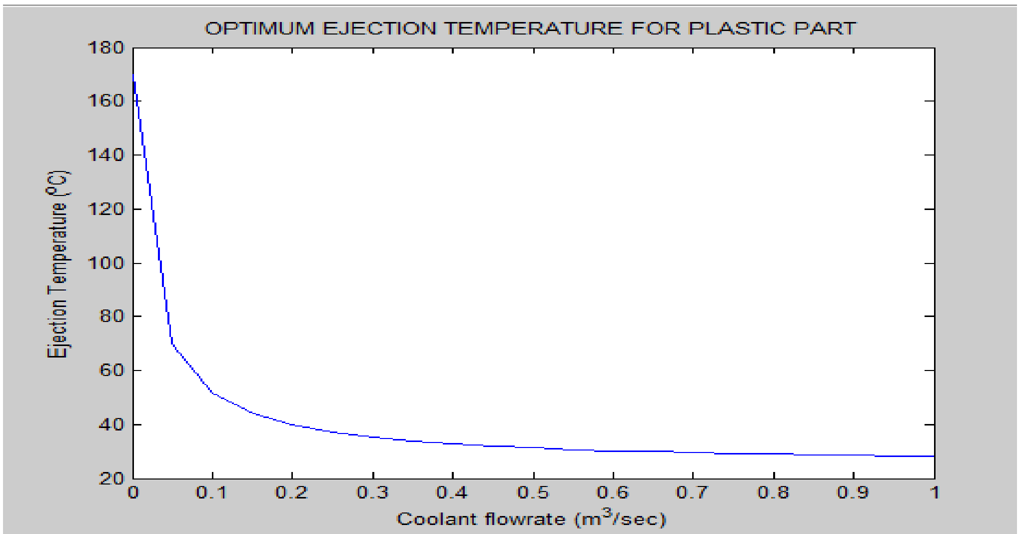

Fig. 1 Ejection Temperature against Volume flow rate (using MATLAB program)

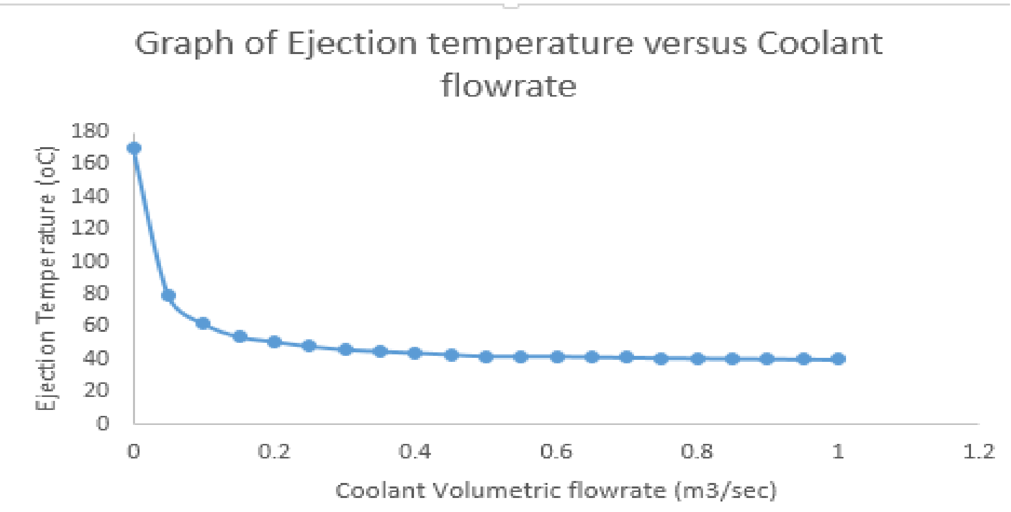

Fig. 2 Ejection Temperature against Volume flow rate (using Excel 2013, program)

From fig. 1 and fig. 2, it is clear that the optimum temperature at which the plastic part is safe to be ejected (at 40^0C) corresponds to the coolant volumetric flow rate at $0.55m^3$/sec, at constant coolant ambient temperature, half plastic thickness and cycle time. This resulting optimum temperature forms the reference control point for the electrical control, to START and STOP the circulation of the water, and also the basis for the electrical system simulation.The result of different half plastic thickness and the corresponding values of ejection temperature when the coolant flow rate, cycle time and ambient coolant temperature are kept constant, using matlab and excel software for the analysis, is shown in the table 2 below.

Table -2 Half Plastic Thickness and Ejection Temperature

S/N	**Half Plastic Thickness (P_1) in meter**	**Ejection Temperature (T_{eject}) in 0^0**	**S/N**	**Half Plastic Thickness (P_1) in meter**	**Ejection Temperature (T_{eject}) in 0^0**
1	0.0003	24.28	7	0.0018	34.82
2	0.0006	26.63	8	0.0021	36.35
3	0.0006	28.35	9	0.0024	37.85
4	0.0009	30.02	10	0.0027	39.31
5	0.0012	31.66	11	0.003	40.74
6	0.0015	33.26			

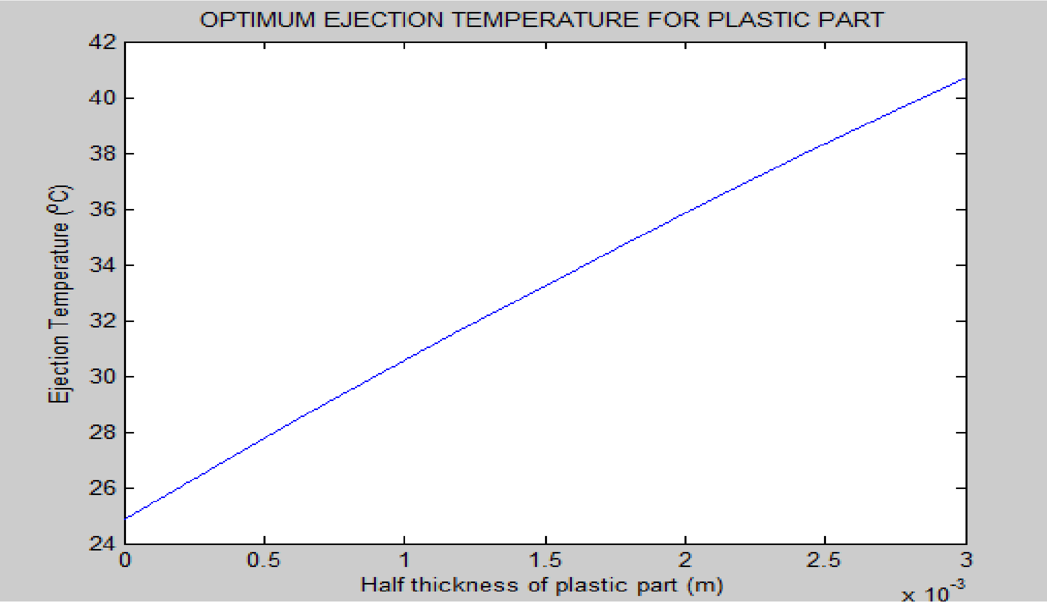

Fig. 3 Ejection Temperature against Half Thickness of Plastic Part (Using MATLAB)

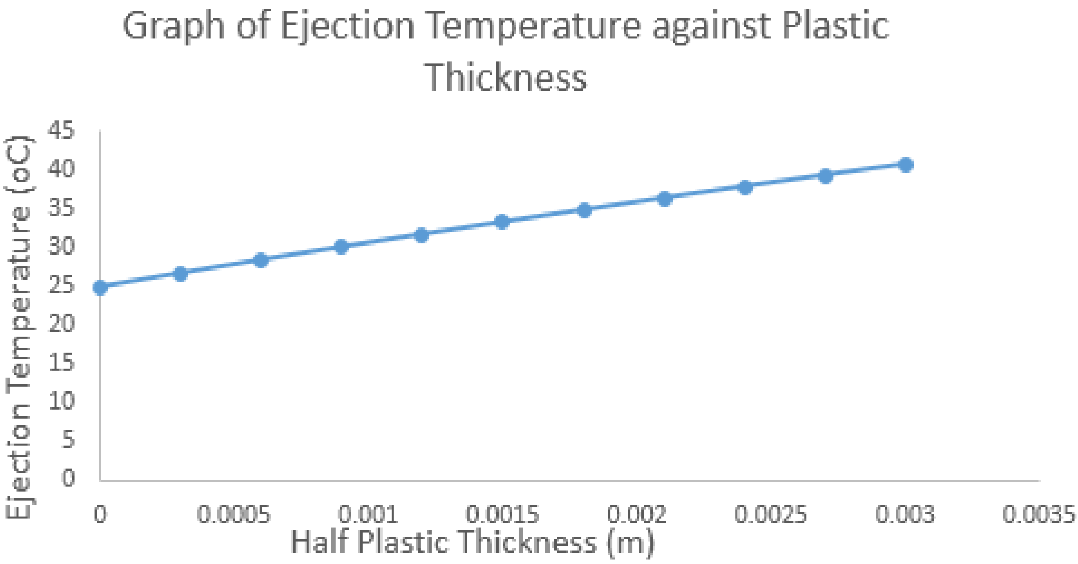

Fig. 4 Ejection Temperature against Half Thickness of Plastic Part (Using Excel)

The resulting curves from both graphs are straight lines, indicating that the plastic thickness is directly proportional to the ejection temperature as obtained from the analysis using matlab and excel. It shows that to keep the optimum temperature constant, the coolant temperature has to be varied by keeping it extremely cold below 25^{0}C. The slope of this graph is: $\frac{\Delta T_{eject}}{\Delta \text{plastic thickness}}$ in$\frac{°C}{m}$.

MODELLED SYSTEM OPERATION

The raw material (propylene) needed for the production, will be fed/melted in the barrel with the aid of three banded heaters attached to the barrel at a temperature of 175^{0}C. The molten product will be injected into the mould as indicated by the glowing yellow LED, through the movement of the extruder inside the barrel. The mould absorbed the heat from the molten propylene causing the mould temperature to rise above the pre-set optimum temperature(40^{0}C) to a corresponding volumetric flow rate (0.55m^3/sec) which causes the actuation of the cooling section as indicated by the blue LED and running of the motors automatically. The return of the hot water from the mould until temperature falls back to the preset optimum temperature with the aid of cold water circulation which is represented by the red LED causes the molten plastic in the mould to solidify to the desired shape. This process of injection mould cooling keeps repeating itself automatically without human intervention to save time, energy and cost of production. This process as explained makes the project an automatic water circulation of an injection moulding cooling. The circuit diagram of the simulated cooling flow is shown in figure 5 below.

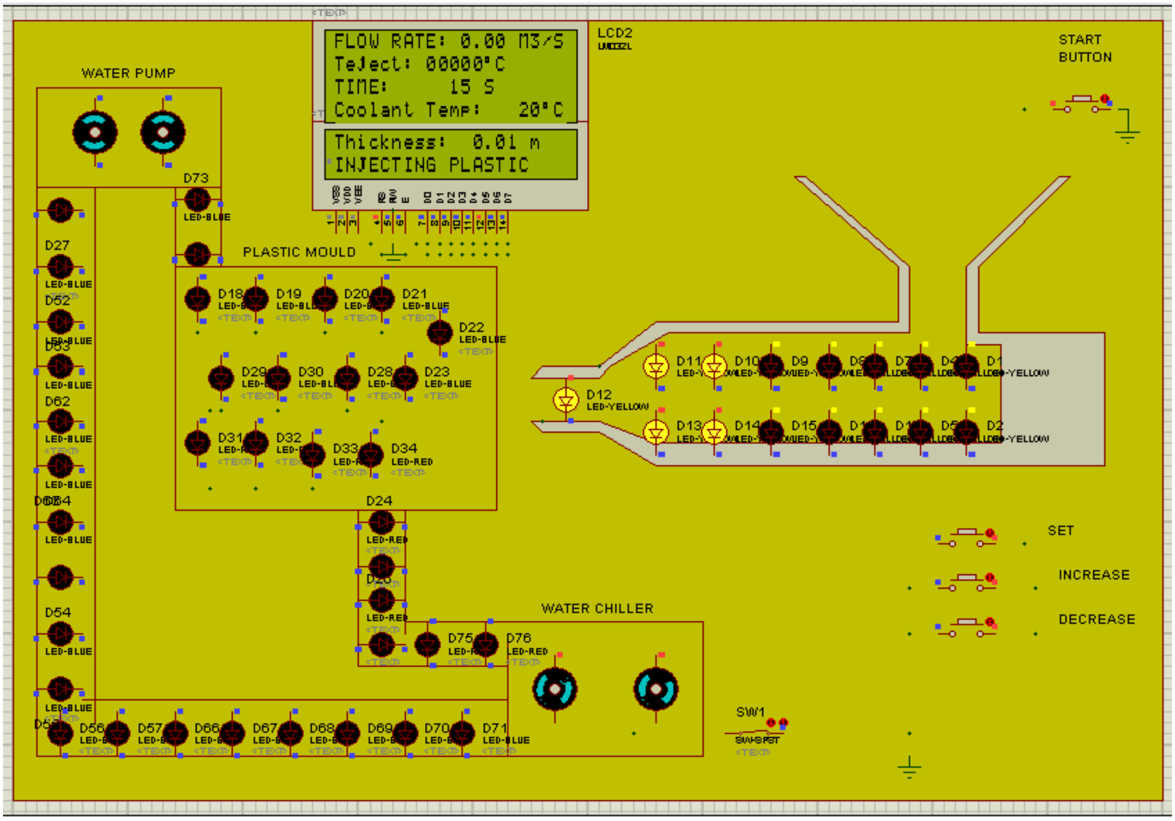

Fig. 5 Circuit diagram of the Simulated Cooling Flow (Using Proteus)

CONCLUSION

Automated mouldcooling is very desirable in injection moulding manufacturing system. This is because it ensures controlled cooling of the product according to the specified temperature, thereby ensuring improved product quality. It also ensures that the processing time is optimum and the temperature distributionis uniformand hence minimises residual stresses and undesired defects in the product and maintains dimensional accuracy and stabilitythat influence the quality of moulded part.It is more economical than the manual mould cooling method by removal of drudgery and maintenance of uniform cooling process.

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