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DEVELOPMENT OF A COOLING DIE USED IN PLASTIC PIPE PROCESSING: NUMERICAL AND EXPERIMENTAL ANALYSIS

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ABSTRACT

In this study, cooling of a plastic pipe-end during a hot-forming process that is one of the commonly used forming methods in plastic pipe production to get seal housing place (muff) was investigated numerically and experimentally. The aim of this study was development of a cooling die that has higher cooling performance and easier manufacturability. Cooling is supplied by the circulation of conditioned water in the channels located in the die in plastic production. The geometry of these channels and mass flow rate and temperature of the cooling water are the parameters affecting the quality of the formed region and process time. In the study, experimental analyses were performed, then numerical analyses were realised and validated with the experimental results for the existing die geometry. Continuity, momentum and energy equations were solved all together and heat transfer was investigated. After validating the model, a few different alternative die models were proposed and analysed to get an optimum which has highest cooling capacity and process ability. At the end of these studies, optimum alternative die geometry was determined. The channels in the suggested die were developed to increase the homogeneity of the cooling by changing the existing channel's shape which can be produced by only longitudinal holes. A simple production method was also suggested for the new die to locate the channels following the circumference of the pipe, like conformal cooling channels. Additionally, aluminium material was also used to decrease the pipe temperature and die weight in the analyses. In conclusion, although cooling process time and mean temperature of the pipe-end were 30 secs and 43.9 ^{o}C respectively for the existing cooling die, these values were determined as 30 secs and 39.5 ^{o}C for the optimised aluminium die. If the temperature of the cooled pipe is taken as the same with the existing cooling, the cooling time decreases to around 20 secs for the suggested die. The weight of the die was reduced from 86.57 kg to 16.22 kg.

Keywords: *Plastic Pipe, Muff, Hot-forming, Cooling, Numerical and Experimental Analysis*

INTRODUCTION

Extrusion which is a very well-known process used to produce objects having a uniform cross-section along the axis is the manufacturing method for thermoplastic pipes. The main principal of pipe extrusion is to transform the solid polymer pellets into homogeneous melt and after that pump the melt through a die having desired cross-section with a constant flow rate [1]. There are cooling units located just after the extrusion machine to cool the pipes down by keeping the molecular regularity. During this process, depending on the needs, there could be some additional auxiliary equipment such as cutting, end-forming, marking etc. In the wastewater pipe production line there must be an end-forming unit to get a shape suitable for joining.

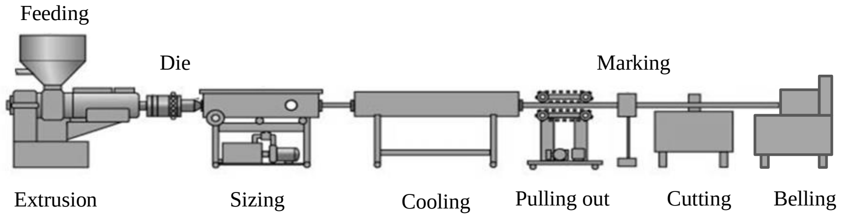

Figure 1. A conventional pipe extrusion line and a belling machine

For pipeline systems there are many different joining types in the usage such as butt-welding, electro-fusion welding, extrusion welding, bell-mouth (pipe socket) fittings, spigot and socket joint etc. These methods are preferred depending on the type of the application.

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Bell-mouth (muff) fittings are generally used for plastic wastewater pipe systems [2], [3]. For this fitting method, one side of the pipe is left as spigot and other side is shaped as a socket in which elastomeric seals are located to provide the leak-tightness of the fittings. Belling machine shapes the end of pipes (end-forming) for bell-mouth fittings. During this process a seal seat is also created (Figure 2).

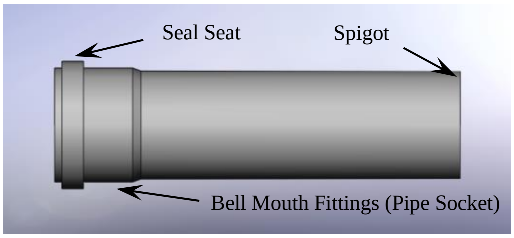

Figure 2. Shaped pipe

Principally, a belling process has two main steps. In the first step, there is a heating unit in which the pipe-end is heated until it can be shaped. The temperature distribution must be homogeneous for the whole surfaces of the pipe-end at the end of the heating phase. After the heating process, the pipe is transferred into the cooling-forming die that has the final requested shape of the pipes to shape it into the socket form as the second step. During the cooling and shaping in the second step, a homogeneous cooling must be applied to the pipe-end. Therefore, cooling dies have special cooling channels in which conditioned cooling water circulates. These channels take the heat out from the pipes. In order to finalize the inside shape of the pipes, a mandrel which has also cooling channels goes into the pipe and finalizes the inside geometry.

If there is inhomogeneous temperature distribution on the pipe, thermal stresses that can bring out some problems during the usage of the pipes such as warpage and cracks occur. That’s why, cooling process is quite important and accurately designed cooling dies must be used [4], [8]. In any thermoplastic forming method, surface quality, dimensions and cycle time of end-product are all dependent on cooling systems.

In the literature, there are several studies about “cooling optimization and increasing cooling rate” and “determination of cooling effects on plastic quality”. In the following lines, some of them are argued briefly to give the approach of the researches on this subject.

Park and Kwon [5] studied on the development of an optimal cooling system for injection moulding process by using computer aided analysis. The optimization was done by minimizing cooling time and increasing temperature uniformity of the part. They optimized the cooling system using special boundary integral formulation and design sensitivity analysis. In the study, three different problems were analysed and three different suggestions were given to see the applicability of their optimization.

In another study, a modular design suggestion for the development of conformal cooling channels was given. The channels were located so close to the surfaces of the cavity and the mould divided into regions which were connected each other with another channel system. Each of these regions was analysed separately and during the analysis, transient heat transfer, temperature and pressure drop through the channels and strength of the mould were taken into consideration as constraints. The authors improved the cooling time with their suggestion shown in the Figure 3 [9].

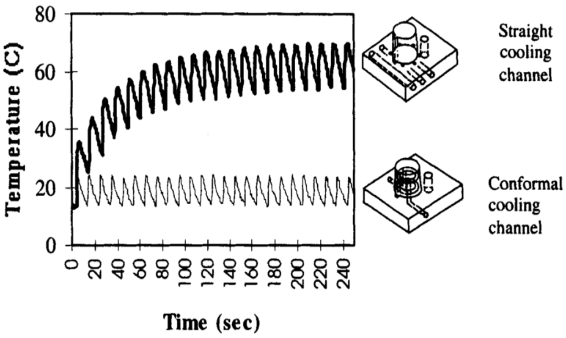

Figure 3. Improvement of the cooling time with conformal cooling channel [9]

In their study, Altan et al. [10] studied forming of conformal cooling channels by means of rapid tooling methods such as powder sintering.

Li [11] suggested a new design strategy decomposing the geometry into simpler features. After optimization of each feature's cooling separately, the entire mould's cooling system was optimized. A recognition algorithm was developed to decompose the entire geometry by taking into account of cooling.

Rapid prototyping and rapid tooling methodologies were investigated for different materials by Ferreira and Mateus [12]. During the studies, the moulds which have conformal cooling channels and are from different composite materials were analysed. Due to less mechanical resistivity than steel, they called the process as soft-tooling. They demonstrated different features and devices for soft-tooling of these alternative materials.

By using thermal analysis with FEA, Dimla et al. [13] optimized cooling process by suggesting a conformal cooling/heating channel for an injection mould. As a result of their analyses, the cycle time of the mould was significantly reduced by conformal cooling and the surface quality of the end product was better than all the other conventional cooling/heating systems.

The importance of cooling on quality and cycle time reduction in plastic processing was emphasized by Li and Li [14] in their study. They developed a cooling system layout design approach by using genetic algorithm and they called this approach as C-space (configuration space) method.

Hassan et al. [7] studied numerically the effect of cooling channels' design on the heat transfer rate in injection moulding process with a time dependent 3D analysis. According to the results, the channel having the same flow rate and rectangular cross-section which is the same area with square and circler ones has better cooling performance (3%), and the one close to the surface has better cooling efficiency than the others.

Au et al. [15] pointed out the impact of the cooling channel design on the production time and end product's quality. They also explained the reason of which the channels must be shaped with straight bored holes as the limits of conventional tooling processes. Additionally they mentioned that although there are new technologies to manufacture complex cooling channel geometries, there is not enough satisfying design approaches. In this study, an automatic design method was suggested and hence an optimum cooling channel was formed by using a visibility method.

An algorithm to generate an optimum conformal cooling channel was suggested by Wang et al. [16]. And they formulated the relationship between conformal cooling and the geometry of the channel. In the study, the results were compared with moldflow analyses.

Matsumori and Yamazaki [4] concluded that; 1- curved cooling channel along the part significantly affect the cooling ratio, 2- differences in cooling ratios cause different stress residuals affecting the shrinkage behaviour of the part, 3- the cooling ratio is controlled by the location and shape of the cooling channels, flow rate of the coolant and mould temperature, in their study which is cooling channel optimization to increase the cooling ratio of a mould.

Sánchez et al. [17] experimentally investigated the effect of cooling on warpage. According to the measurements, the authors showed that warpage is significantly dependent on melt temperature, cooling channel design and cooling time.

Hsu et al. [6] tried to answer the question of "Why does inhomogeneous cooling arise on a cooled plastic part?". In the study, they used a 3D simulation program (Moldex3D) to compare conventional and conformal cooling channel layouts' performance and found the results; a- If cooling channels can be located equal distance to the cooled part, the cooling time will be shorter, b- Cooling system design, mould material, coolant type, coolant temperature, and flow rate are the factors affecting the cooling time, c- The system design parameter is the most difficult parameter among the others due to the restrictions of the conventional mould making methods. It is not possible to form any conformal channel inside the mould with traditional techniques.

In another study, authors reviewed the literature on conformal cooling and rapid heat cycle. Rapid heat cycle can prevent the weld line and increase the surface quality of the part and give a possibility to use longer flow lengths [18]. Rapid heat cycle moulding (RHCM) was investigated together with cooling of a highly complex and big automotive interior part's injection mould by Wang, Zhao and Wang. FEA techniques were used to simulate the heat transfer and to see the performance of the alternative cooling/heating designs. A mathematical model was also derived to predict the thermal response by regression analyses. Additionally, surface temperature differences' effect on quality was also investigated experimentally. In this study, a baffle-based heating/cooling channel was suggested instead of conformal cooling channels. If the surface temperature of the cavity is high enough, the quality of the part's surface is getting better [19], [20].

To prevent warpage especially in thin-walled parts during injection moulding process, a local temperature control is needed. To show this behaviour and find a possibility to set any required temperature at any point in the mould, a cooling method was suggested by Nian, Wu and Huang [21]. Moldex 3D analyses were used and experimental studies were realised.

An aluminium extrusion die having a cooling system in was studied. By using laser melting process, a conformal cooling channel was formed in the die. Some extrusion trials were realised with and without cooling and compared with the analyses. According to the result, the speed of extrusion with cooling was three times better than without cooling one. But extrusion force increased slightly [22].

An automatic design process for cooling system of a mould was developed by Becker and Wits [23]. Computer Aided Synthesis (CAS), Set-Based Concurrent Engineering (SBCE) and Just in Time Decision Making (JIT-DM) were used to develop suggested method.

In the study performed by Wu et al. [24], optimisation of a conformal cooling in a mould was investigated. Numerical and experimental analyses were realised and a topology optimization algorithm were suggested to decrease the weight of the mould and increase the cooling performance. Additionally material properties were also studied.

Conformal cooling advantages and alternatives were studied by Vojnová [25]. The comparison of conformal and conventional cooling on product quality and cycle time and manufacturing methods were investigated as well. Direct metal laser sintering method was used to produce required conformal cooling channels.

In the other study, conformal cooling channel formed by milling process and having rectangular cross-section which has the same area with circular alternative channels was proposed and compared with the other types of cooling channels such as traditional straight-bored holes. Examination of warpage and cooling time was realised. The numerical analyses performed by Moldflow [26] were agreed with the experimental results and reduction of warpage and cycle time (65%) was gathered.

Jahan and El-Mounayri [27] proposed a systematic method to use conformal channel for injection moulding instead of conventional straight-drilled channels. In their study, a numerical model was developed and validated and by using design of experiments, alternative geometries were studied. At the end, an alternative design was suggested.

Out of injection moulding process, there are some other forming processes which are using cooling channels such as in the study performed by Behrens et al. [28]. Cooling channel development for hot forging process was studied by Behrens et al.. and as a result a forging die was suggested. Two different die alternatives were analysed numerically and the results were given in the paper.

In another study, numerical analyses and topology optimization methods for developing conformal cooling channel instead of traditional cooling channels were studied and validated by experiments [29].

By using DOE (design of experiments), thermomechanical optimization of the mould was investigated by taking into account mechanical resistivity and additionally a state of the art technique for conformal channel design was obtained [30].

A few alternative conformal cooling channel designs were investigated and a proper one chosen which gives uniform cooling and better cycle time. FEA was used to analyse thermal stresses [31].

To decrease the cooling time of a mould, a special insert having higher thermal conductivity was suggested and numerical and experimental analyses were realised to see the performance of it [32].

An injection mould of a part which has a complex and variable thickness was investigated in this study. By implementing conformal cooling channel on this mould, the cycle time reduced 30% compared to traditional cooling channels [33].

Optimization of conformal cooling channel and topology of the mould were studied numerically and experimentally. Thermomechanical optimization for the channels and multiscale topology optimization was realised [34]. Conformal cooling channel and traditional straight bored channel were compared for an injection mould of a battery casing part. Surface quality, warpage and cycle time were investigated [35]. Cooling of a mould was investigated by artificial neural network technique (ANN). The mould cavity surface temperature was predicted by ANN approach [36]. Modelling of cooling time was suggested and the model was validated with experimental results [37].

In this study the cooling process was studied both experimentally and numerically for the aim of developing more efficient cooling die. The measurements were taken on the field during the pipe production was continuing. The numerical model was solved by using the Ansys Fluent software. Both results were discussed in detail and an improved die was suggested for the belling process. Accordingly, the temperature changes by the time were simulated, heat transfer from the pipe was discussed and the temperature distribution was also studied.

The purpose of this study is to analyse the cooling process of the existing system and examine the time of cooling process and hence to improve the cooling die by getting insights from the literature which briefly given in this text in order to decrease the processing time and increase the quality of the end product. The cooling performance depends on time, coolant temperature, mass flow rate, and shape of the cooling channels. In this study, optimization of the cooling channels was aimed to increase the temperature homogeneity of the formed pipe-end and decrease the cooling time. In the current process, the main problem was defined as availability of big temperature differences on the pipe surface during the cooling process and long forming time. Inhomogeneous temperature distribution problem causes increase of production time, low quality of the pipe surface and undesired shrinkage problems as mentioned in the summarised literature.

PROBLEM DEFINITION

The most prominent step of the belling process affecting quality and production period is the cooling process. The cooling time takes the biggest share of the total production time of a thermoplastic part in any thermal process [8]. For instance, in injection moulding, the cooling time is more than half of the total production time (Figure 4). The belling process is similar to the injection process except for the injection step. Instead of the injection step, there is heating in the die. In the cooling step of a belling process, both shaping and cooling are performed together simultaneously.

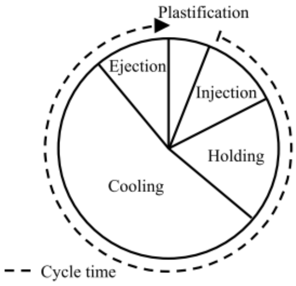

Figure 4. The cooling time and the other steps in an injection process [8]

It is one of the biggest challenges to get requested shape quickly in the current belling machines. A homogeneous temperature distribution of die surface could not be reached and due to that reason, the production period is getting longer. Moreover, the production of the dies is very difficult because of a lot of drilling process to get channels by using straight bored holes.

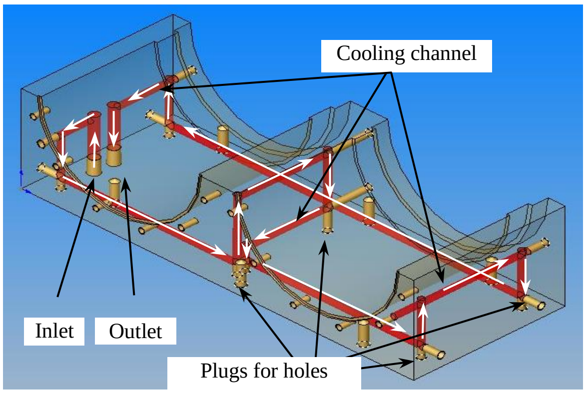

Figure 5. Cooling channel created by straight holes

The cooling channel created by drilling process can be seen from Figure 5. To build this channel, firstly, the holes are drilled and then some plugs are used to close some exits. The aim of building this channel is to be as close as possible to the surface of the die holding the pipes like in injection moulds [38]. Thus, a homogenous temperature distribution is targeted. However, drilling only straight holes through the metal body doesn't give us a chance to expose homogenous cooling because of not being able to follow the curved surfaces with the cooling channel. Additionally, using only one channel through the whole die causes the temperature increase from inlet to outlet. Thus, the temperatures of the dies will have different values in different zones. In the Figure 5, the direction of the coolant is shown with white arrows. As can be seen from the figure, the coolant follows only the edges of the curved surfaces of the die. It is not possible to reach in the middle of the surface and especially the seal seating place which needs much more homogenous and definite temperature distribution.

Numerical and experimental analyses were realised for the existing dies to see the numerical model's performance by comparing the experimental results and then another die was developed to overcome all the mentioned restrictions.

EXPERIMENTAL STUDIES

All the measurements were taken from a working belling machine having a die shown in Figure 5 located in Dizayn Grup Inc.'s pipe production factory. During these experimental studies inlet and outlet temperatures of the coolant, mass flow rate of the coolant, inner surface temperature of the pipe-end and cooling time were recorded (Figure 6).

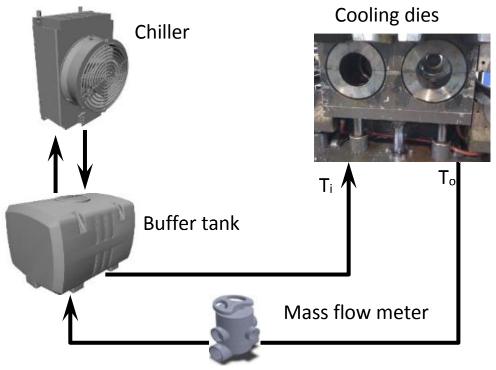

Figure 6. Experimental setup of the cooling of dies

Due to the complexity of the machine and die geometry at the forming station, it was not possible to record surface temperatures of the die accurately. That's why, the validation of the numerical analyses has been done according to comparison of the cooling times, the inner surface temperatures and the outlet temperatures. Experiments were realised on polyethylene and polypropylene pipes having 50 mm, 75 mm and 110 mm outer diameters. The dimensional details of the pipe and the other parameters of the system can be seen in Table 1.

Table 1. Measured values during the tests

	Case 1	**Case 2**	**Case 3**
Material Type	PE	PP	PP
Pipe Diameter	DN 50	DN 70	DN 110
Pipe Thickness	1.80 mm	1.9 mm	2.7 mm
Temperature of the Pipe before the Cooling	90.2 ° C	90.9 ° C	91.1° C
Temperature of the Pipe after the Cooling	50.1 ° C	50.8 ° C	51.1 ° C
Cooling Time	20 s	25 s	30 s
Mass Flow Rate of the Coolant	0.018 kg/s	0.0195 kg/s	0.034 kg/s
Inlet Temperature of the Coolant	18 ° C	18 ° C	18 ° C
Outlet Temperature of the Coolant	20.9 ° C	21.1 ° C	20.8 ° C

To get more realistic test results, the test system was settled on the production line and hence the measurements were taken while the pipes were being manufactured. Inlet and outlet water temperatures of the coolant and flow rates were measured by thermocouples located into the coolant pipe. All the measurement equipment, such as thermocouples and mass flow meters, has been calibrated in Mir Research and Development Laboratories by using reference calibrated equipment.

NUMERICAL STUDIES

Non-linear transient differential equations were solved by using CFD. Conservation of mass, momentum and energy equations were written in the form of partial differential equations which were discretized by Fluent Solver [39]. After setting the boundary conditions of the problem, the solution and then post-processing was realised by Ansys Fluent Program. To get mesh independency of the solution, fluent relaxation parameters were tightly adjusted, the cell numbers of the whole geometry were increased as much as the results start to be nearly the same with the preceding cell numbers' results and mesh quality was increased as well.

Fluid Flow and Heat Transfer Equations

The partial differential equations that were used to express the fluid flow and heat transfer are continuity equation, the Navier-Stokes equations, and energy equation [40]. All these equations were solved simultaneously during the simulations.

Continuity Equation;

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{1}$$

Momentum equation;

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{2}$$

$$\bar{\bar{\tau}} = \mu \left[(\nabla \vec{v} + (\nabla \vec{v})^T) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \tag{3}$$

Energy equation;

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\vec{v}(\rho E + p)\right) = \nabla \left(k_{eff} \nabla T - \sum_j h_j \vec{J}_j + \left(\bar{\bar{\tau}}_{eff} \cdot \vec{v}\right) \right) + S_h \tag{4}$$

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{5}$$

CAD Model of the Cooling Die

CAD model of the die was created by Solidworks and simplified to make analyses accurate and needing less computation time. Although the real die (Figure 7) made of different metal parts, the model was built as one part containing the cooling channel in it. All touching bodies were taught as bonded and the contact resistivity was neglected.

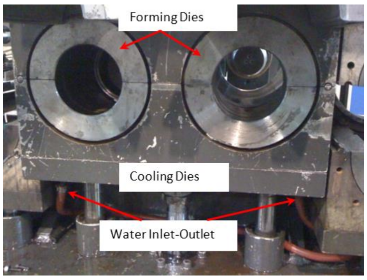

Figure 7. The die as it is mounted to the machine

As mentioned above, the aim of the cooling die is to provide a homogeneous cooling process. To reach that mentioned aim four different cooling channel arrangements were investigated. These suggestions' and existing channel's shapes can be seen in the figures below. Instead of creating circular drilled holes (Figure 8-a) which are not able to follow the curved surfaces as a channel, the suggested channels contain rectangular flow cross section following the surfaces through the pipe circumstances. Thus, in every points of the channel, the distance from the pipe surface to the channel is about the same (Figure 8-b). In the other embodiment of this solution, to get more homogenous flow inside the channel, the baffle plates are located as seen in Figure 8-c. With this arrangement, the direction of the coolant coming into the die from the inlet could be changed to the perpendicular direction homogenously. With the third suggestion, every pipe sections are cooled separately by dividing the die into two separate channels which contain baffle plates (Figure 8-d). The last alternative includes small parallel rectangular channels following the circumstances of the pipe (Figure 8-e). Hence the velocity of the coolant will increase, and more homogenous flow velocity profile could be reached in each rectangular channel.

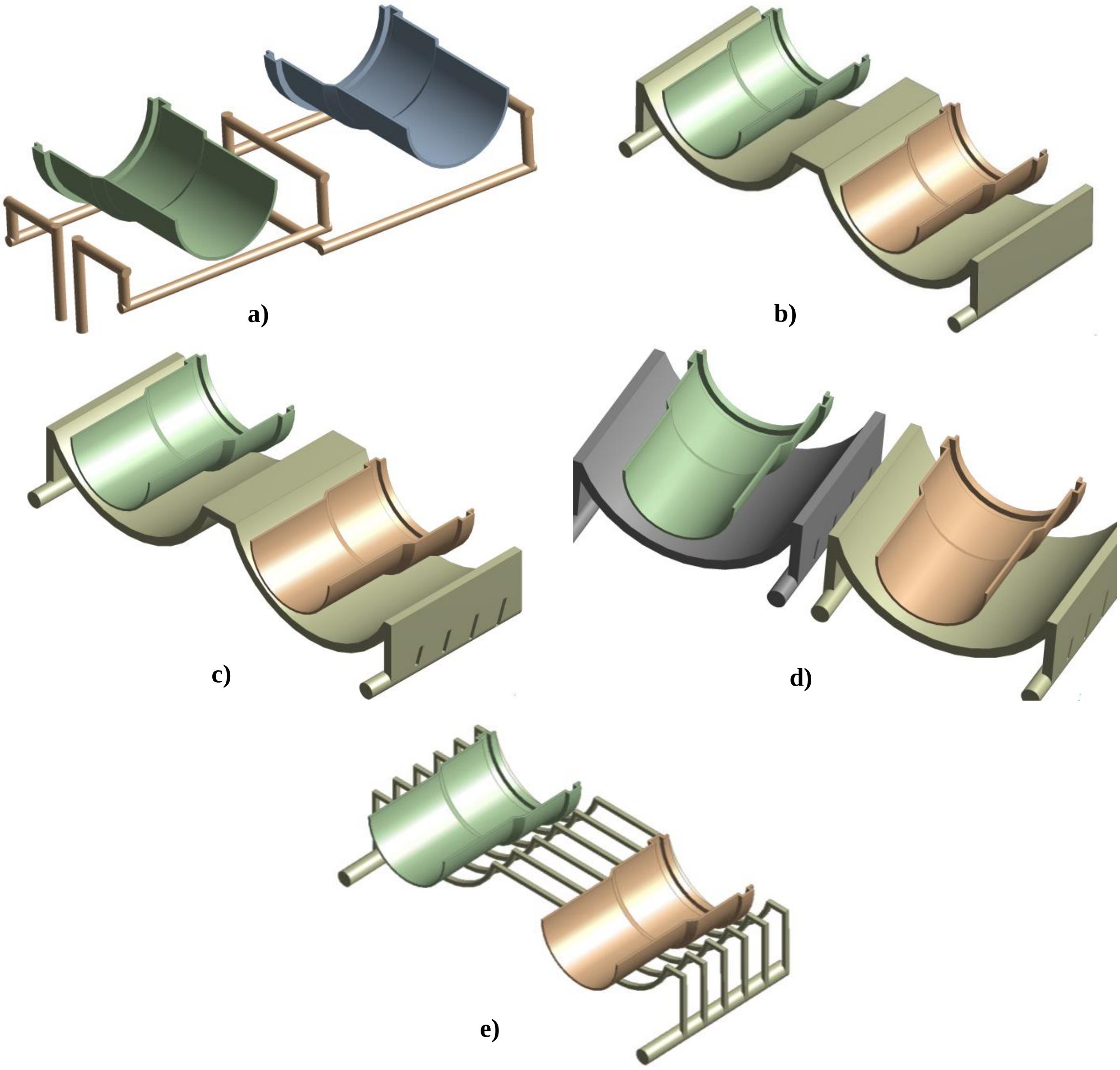

Figure 8. **a)** Existing arrangement, **b)** Alternative arrangement – 1, **c)** Alternative arrangement – 2, **d)** Alternative arrangement – 3, **e)** Alternative arrangement - 4

Mesh Generation

Since only the heat conduction equations were solved in the analyses, there was no need to increase the number of meshes of the die. However, the mesh numbers of coolant zone must be sufficient so that the heat transfer coefficient can be accurately determined in the cooling channel. For the solution independence of the mesh, the internal flow was analysed separately. The number of mesh was increased in the consecutive analyses and the mesh sizes were decreased in the channels as they approach the surface. After the mesh independent solution was realised, the final solutions were made with the decided number of the mesh.

To say that a solution is independent of the mesh, at least two criteria need to be checked. One of these criteria is the results of normalized continuity, velocity, energy, k and epsilon residuals, and the other is the closeness of the results obtained by successive analyses. Although the residual values are suggested to be smaller than 10^{-3} [40], the values was targeted to be smaller than at least 10^{-4} in the analyses and final analyses were made with the mesh that provides this constraint. During the analyses, residual was less than 10^{-4} for the continuity equation, it was less than 10^{-5} for the turbulence parameters and it was less than 10^{-6} for the energy equation. In Figure 9, the realised residuals change was plotted.

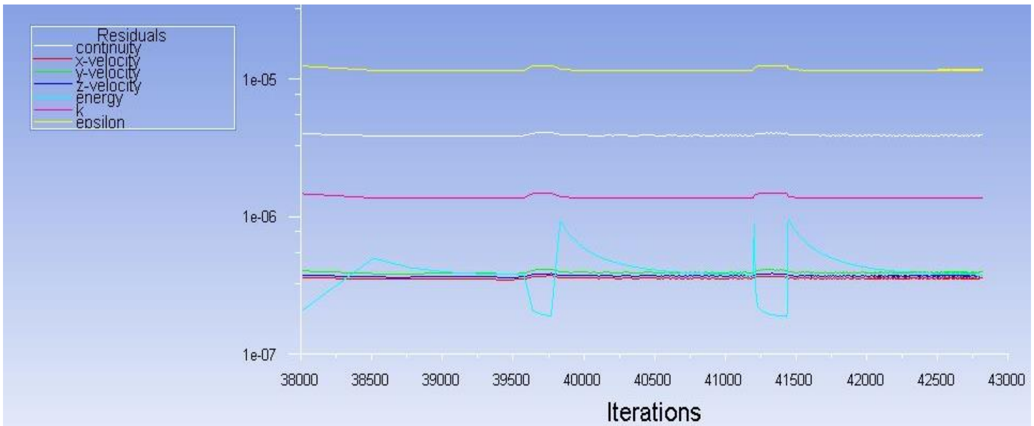

Figure 9. Residuals plot

To reach a mesh free solution in the flow in the channel geometry, different mesh numbers were analysed. In the analyses, the channel outer surface was given a constant heat transfer coefficient (7 W/m^2K) and the water-inlet temperature was set 291.15 K. First, the initial temperature of the channel was set 364.15 K and then time dependent analyses were realised for different mesh numbers for 30 seconds. In the figures below (Figure 10, Figure 11, Figure 12), temperature changes in time are given for each mesh numbers.

In these analyses, the maximum size of the mesh elements in the channel was defined as the mesh quality. For example, in the "Mesh 2 mm" analysis shown in Figure 10-a, the largest dimension of one edge of the largest element forming the channel was a maximum of 2 mm. The final mesh properties of the geometries according to this approach are given in Table 2.

Table 2. Mesh properties of different channels

	Alternative Arrangement - 4		**Existing Arrangement**		**Alternative Arrangement - 1**	
Maximum Element Size	**nodes**	**elements**	**nodes**	**elements**	**nodes**	**elements**
2 mm	368.512	231.993	63.113	285.779	587.547	1.742.001
1,5 mm	838.976	549.230	82.619	394.698	1.196.802	3.961.629
1 mm	2.761.598	1.883.627	258.874	1.330.795	3.280.547	12.659.485

As it can be seen from the following figures, the selected mesh numbers do not affect significantly the output temperature in the existing channel and alternative – 4. However, as the number of mesh increases in alternative – 1, the output temperature is slightly higher. For this reason, all analyses were carried out by taking the mesh size 1 mm in alternative – 1 and in other alternatives. Additionally, average wall y+ value and skin friction coefficient of existing geometry having turbulent flow is 4.17 and 0.012 respectively. It is possible to decrease y+ value by increasing the boundary layer mesh quality, but it takes more computation resource and time. Instead of increasing the quality, enhanced wall treatment function was used for turbulence model, and hence, reasonable numerical results were taken.

As mentioned above, all modelled alternatives were meshed with a maximum element size of 1 mm. Five-layer inflation was applied with 1.2 growth-rates in channel sections. Hence, the boundary layer was solved more accurately. In addition, since the different zones were defined as coupled with each other, the transitions were extremely smooth as shown in the figures (Figure 13, Figure 14, Figure 15). Therefore, the solution was much more accurate and the temperature distributions were more realistic.

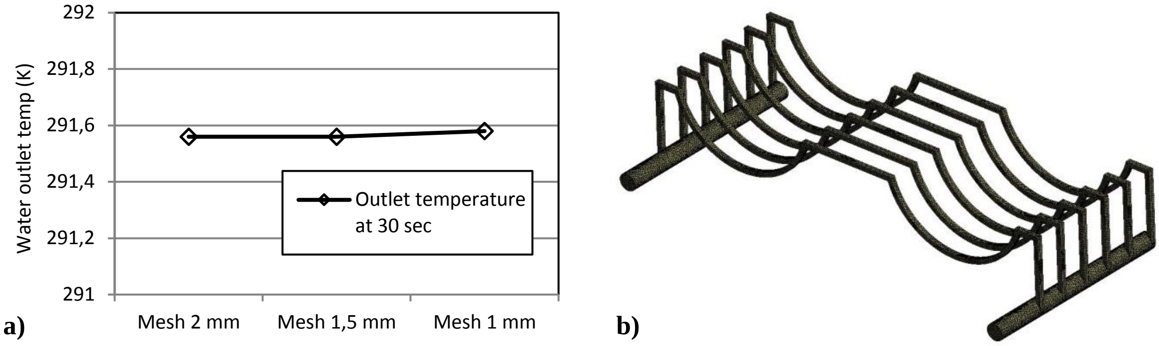

Figure 10. a) Outlet temperature of alt. arr. – 4, **b)** Meshed channel of alt. arr. – 4

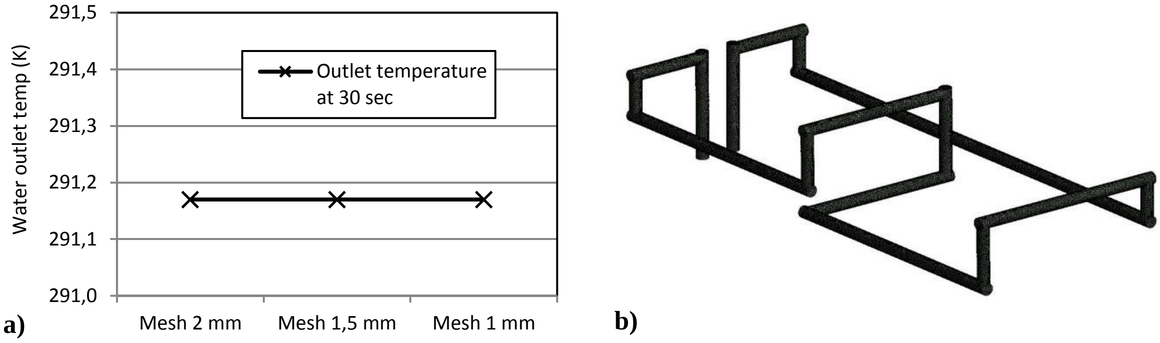

Figure 11. a) Outlet temperature of existing arrangement, **b)** Meshed channel of existing arrangement

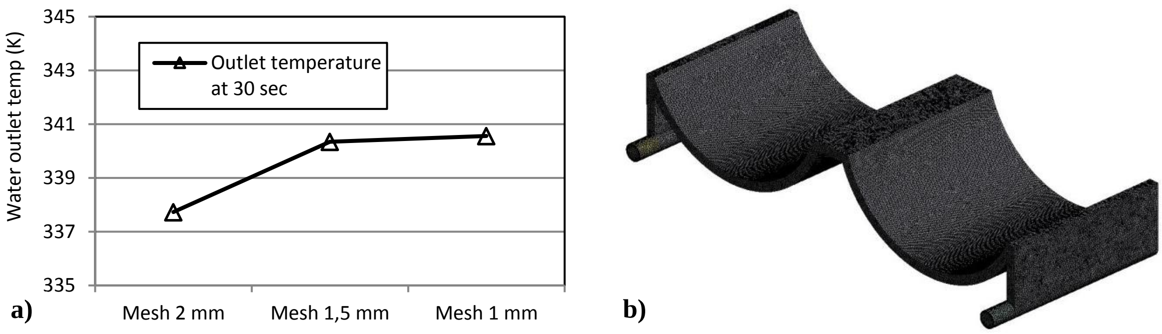

Figure 12. a) Outlet temperature of alt. arr. – 1, **b)** Meshed channel of alt. arr. – 1

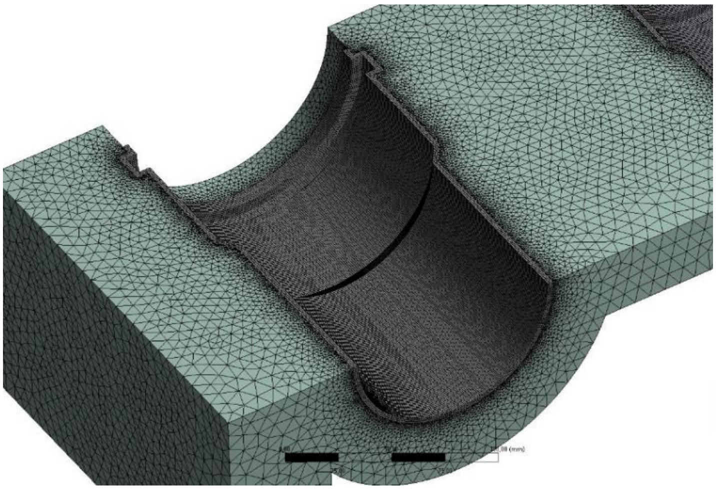

Figure 13. Coupled mesh

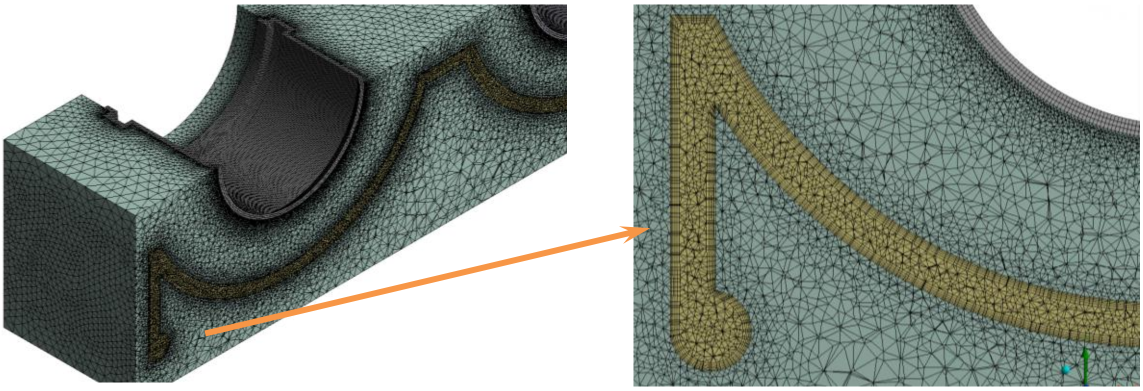

Figure 14. Growing mesh from the walls in alternative arrangement – 1

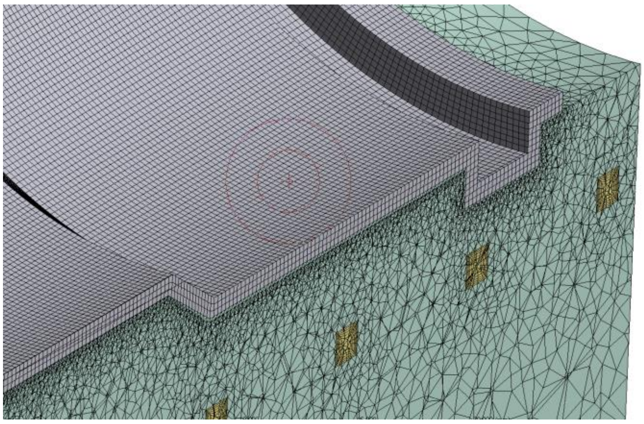

Figure 15. Mesh details of alternative arrangement – 4

Boundary Conditions and Solution Methods

Pressure-base and transient solution was used for the analyses. Since the flow rate was low enough, the laminar solution was set for all the alternatives except existing geometry which is turbulent and the energy solution was activated. Standard k-epsilon turbulence model and enhanced wall treatment function (because of y+>1) was used for turbulent analyses. Reynolds numbers of the alternative geometries are given in Table 3. The properties of the mould; density is 7850 kg/m^3, specific heat is 460 J/kgK and thermal conductivity is 42 W/mK. For plastic pipes, density is 905 kg/m^3, c_p is 2000 J/kgK and thermal conductivity is 0.21 W/mK. In addition, analyses were also made for aluminium as a different metal material in the study. AL6061, which is widely used in moulding, was taken as an aluminium material and its density is defined as 2700 kg/m^3, specific heat of 896 J/kgK and thermal conductivity of 167 W/mK. The model was divided into four separate zones, named as mould, right pipe, left pipe and water (Figure 16).

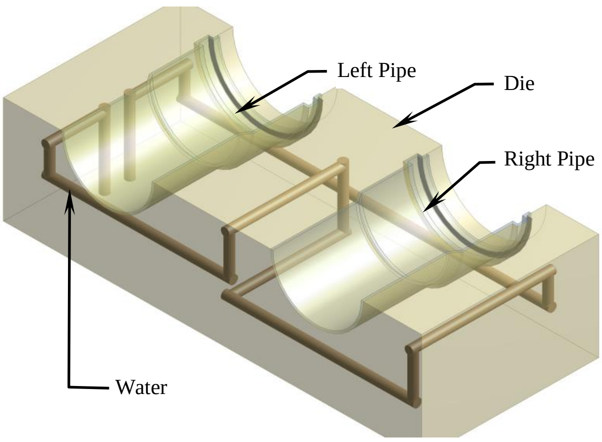

Figure 16. Four volumes of the model

Table 3. Reynolds numbers of the alternatives

Alternative Arrangement - 4	Existing Arrangement	Alternative Arrangement - 1
1075 < 2300, laminar	4110 > 4000, turbulent	340 < 2300, laminar

Boundary conditions were defined as follows;

The mass flow rate of the coolant was 0.034 kg/s and the water inlet temperature was 291.15 K. The channel outlet was defined as outflow and the channel outer surfaces and the die contact surfaces were coupled. Since the mould was symmetrical, half of the mould was modelled and the interface was defined as the symmetry surface in Fluent. At the back of the pipes and on the side surfaces of the mould, the heat conduction was neglected, and the heat flow was defined as zero. On the pipe inner surfaces and pipe end, the heat transfer coefficient was 10 W/m^2K and the air temperature was 298.15 K. In the same way, the outer surfaces of the pipe and the surfaces in contact with the mould were defined as coupled.

While momentum and energy equations were solved as second order upwind, transient equations were solved as first order implicit that is widely used for quickly reaching a stable solution with reasonable results. Pressure-velocity coupling was considered by the SIMPLE method.

Finally, the time step size was set at 0.02 sec and a maximum of 20 iterations were adjusted for each time steps. The initial temperature of the mould and the water was set at 298.15 K and the initial temperature of the pipes was set at 364.15 K. Using Fluent's automatic initialize and modify case feature, simulation of which the mould was loaded with a new hot pipe (364.15) after each cycle was realised automatically until the desired number of cycles. In the analyses, cycle analysis was carried out until the mean temperature of the mould and pipe reached the equilibrium.

Validation of the Numerical Model

After setting the boundary conditions and defining the solution methods, the model was validated with the experimental results of the model having classical cooling channel for different diameters (Φ50, Φ75 and Φ110 mm).

The experimental temperature of the pipe before the cooling process, inlet temperature of the coolant, mass flow rate of the coolant and cooling time were taken as input for numerical validation analyses and after realising successive iterations to reach the steady conditions of the dies, the following numerical results were calculated. According to the results, the outlet temperature of the coolant is very close to the experimental results in which the difference is ±0.2 ⁰ C. Likewise, the numerical temperature of the pipe inner surface after the cooling process is also close to the experimental results with ±0.3 ⁰ C. These differences are acceptable to continue the numerical analysis to define better cooling channel geometry which is the aim of this study.

Table 4. Comparison of the results for validation

	Case 1		Case 2		Case 3	
	Exp	Num	Exp	Num	Exp	Num
Temperature of the Pipe before the Cooling	90.2 ⁰ C		90.9 ⁰ C		91.1 ⁰ C	
Cooling Time	20 s		25 s		30 s	
Mass Flow Rate of the Coolant	0.018 kg/s		0.0195 kg/s		0.034 kg/s	
Inlet Temperature of the Coolant	18 ⁰ C		18 ⁰ C		18 ⁰ C	
Outlet Temperature of the Coolant	20.9 ⁰ C	21.0 ⁰ C	21.1 ⁰ C	20.9 ⁰ C	21.7 ⁰ C	21.9 ⁰ C
Temperature of the Pipe after the Cooling	50.1 ⁰ C	50.3 ⁰ C	50.8 ⁰ C	50.5 ⁰ C	50.9 ⁰ C	51.1 ⁰ C

RESULTS AND DISCUSSION

Since a new hot pipe is placed in the mould after each cooling cycle in the manufacturing process, taking the temperature change for only one cycle (eg: 30 sec) of the mould into account will not be sufficient for accurate analysis. It must be waited for the time required to reach equilibrium temperature of the mould through the cooling cycles. This behaviour was seen in the analyses. Depending on the cooling performance, while the mould warmed up in some alternatives, the mould cooled down in the others over time and after a while they became in balance. This trend can be seen from the mean pipe and the coolant outlet temperatures given in the Figure 17 and Figure

18 respectively. The graphs show the average pipe temperatures, the average pipe inner surface temperatures, and the water outlet temperatures after each cycle through the cooling process. While the average temperature of the pipe can be stable after 4.5 minutes (270 sec, 9 cycles) at 43.9 °C in existing mould, the average temperature of the pipe remains constant at 45.7 °C after 11 minutes (660 sec, 22 cycles) in alternative – 1, and finally in the alternative – 4, the average temperature of the pipe remains constant at 41.6 °C after 8.5 minutes (510 sec, 17 cycles). The temperature change is less than 0.1 °C after reaching stable temperature for all analyses. In alternative – 4 and alternative – 1, the temperature increases in time, while in alternative – 4 the temperature initially increases slightly and then falls in time (Figure 17). Similarly, change in time is seen in the outlet temperature of the cooling water (Figure 18). As a result, it is necessary to wait for the steady state for 9 - 10 minutes after starting the cooling process.

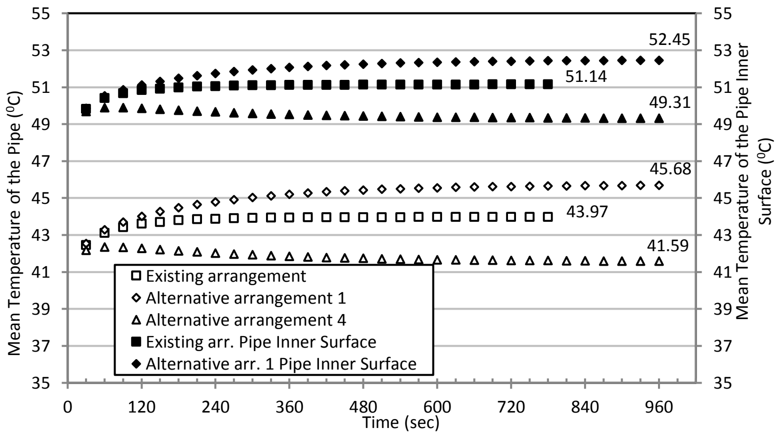

Figure 17. Temperatures of the pipe for different arrangements (^{0}C)

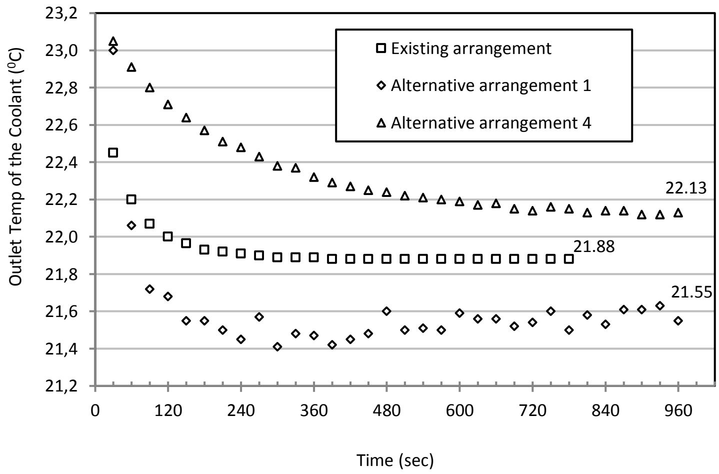

Figure 18. Outlet temperatures of the coolant for different arrangements (^{0}C)

Numerical studies showed that alternative – 2 and alternative – 3 had very close results with alternative – 1 because their flow rates and Reynolds numbers were very low and hence heat transfer coefficients were close to each other. The heat transfer coefficients of the water for these geometries were 551.3 W/m^{2}K for alternative – 2, 630.8 W/m^{2}K for alternative – 3 and 544 W/m^{2}K for alternative – 1. Alternative – 1 was chosen to compare with the other geometries because of the simplicity of its geometry and no detailed analyses were done for unchosen alternatives. Only alternative – 1 and alternative – 4 were used in comparison to existing mould. In Alternative – 1, the coefficient of heat transfer was found to be very low due to the very low water velocity (Figure 19). The heat transfer coefficient of the water in the existing, alternative – 4 and alternative – 1 channel was determined as 5056 W/m^{2}K, 2433 W/m^{2}K and 544 W/m^{2}K respectively. Thus, the cooling performance of the alternative – 1 is even worse than the existing one. In the existing channel, the whole flow is passed through a single small channel, so the velocities are much higher and therefore the heat transfer coefficient is much higher. This can be also observed in the mean pipe temperature and the water outlet temperature results (Figure 17, Figure 18).

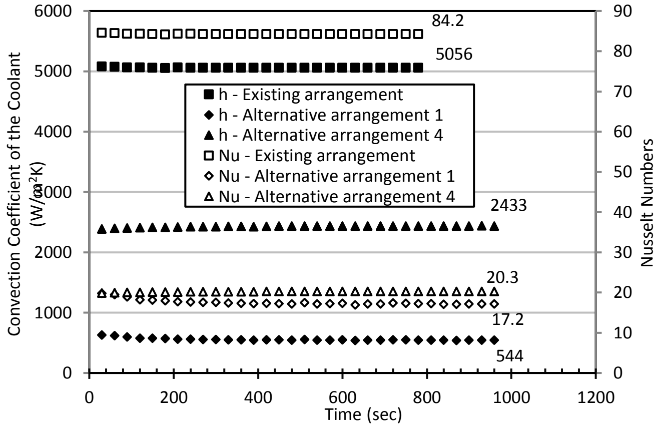

Figure 19. Convection coefficients and Nusselt numbers of the coolant for different arrangements

Nusselt numbers were also calculated and showed in Figure 19. Accordingly, the Nusselt number was 20.3 in alternative-1, 17.2 in alternative-4, and 84.2 in classical channel.

In contrast to the convection coefficient, alternative – 1 produced much better results in terms of pressure drop. Due to the low velocity, the pressure drop was also very low. Accordingly, the pressure drop was 23 Pa in alternative – 1, 592 Pa in alternative – 4 and 3077 Pa in the existing channel. The existing channel is also a disadvantageous solution because of the excess pressure drop. In Alternative – 1, because of the low pressure drop, better cooling can be done by increasing the flow rate. However, increasing flow rate alternative to improve the cooling was not considered because the flow rate studied in this study is constant in the plastic process.

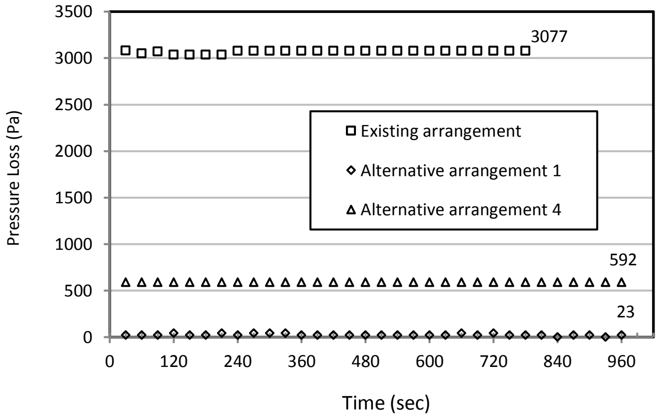

Figure 20. Pressure drop of the coolant for different arrangements (Pa)

The channel geometry given in alternative – 4 was found to be the most suitable from the analyses and after that, additional analyses were performed for less massive alternative – 5 and different mould material such as AL6061 containing this channel geometry to reduce the mould cost and reduce the time to reach steady state.

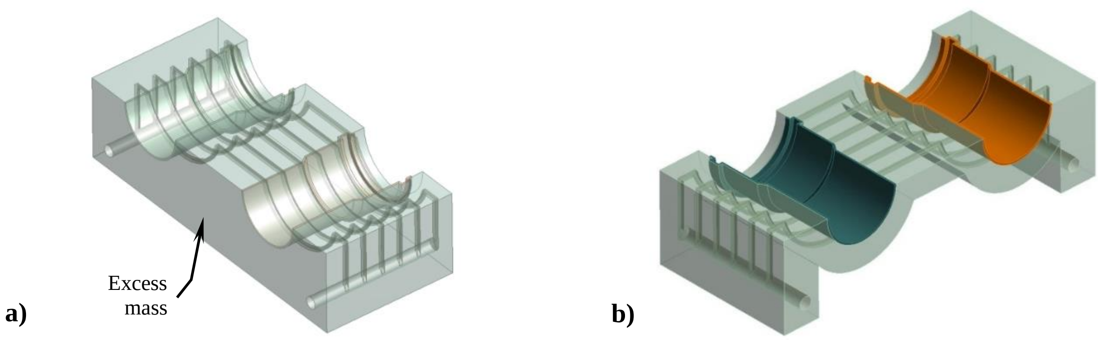

Figure 21. a) Excess mass of alternative – 4, **b)** Alternative arrangement - 5

As it can be seen from Figure 22, when the mass of the mould is reduced, the mould reaches the steady state condition in a shorter time. In both cases, the temperature of the pipe increases at first, then the temperature drops over time. However, in alternative – 5 (Figure 21-b), the pipe is at about 0.3 °C higher temperature than alternative – 4 which has much more material (Figure 21-a). In Alternative 5, the pipe is at 41.86 °C and reaches the steady state condition at 660 secs (22 cycles), while in the alternative – 4, it is at 41.59 °C and reaches steady state condition at 870 secs (29 cycles). The fact that both temperatures are very close together and the duration of the reaching steady state condition (equilibrium) is less (22 cycles) makes it reasonable to use alternative – 5.

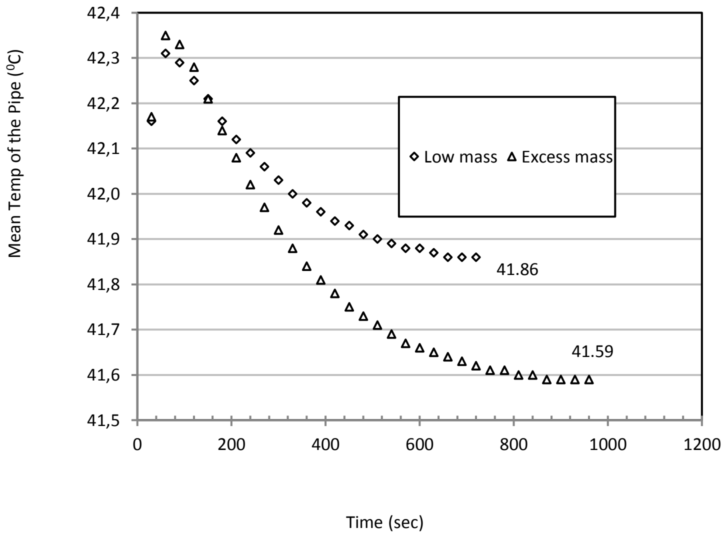

Figure 22. Mass reduction, alternative – 5

After the selection of Alternative – 5, the cooling time per cycle was chosen as 20 secs to see the performance on shortening the cooling process time. According to this, it was observed that the pipe was hotter than the 30 secs cycle time but the total cycle to reach the steady state condition was shorter. The pipe mean temperature decreased to 50.97 ºC at 160 secs (8 cycles) in the 20 secs per cycle time analysis, while the pipe decreased to 41.86 ºC at 660 secs (22 cycles) in the 30 secs per cycle analysis (Figure 23).

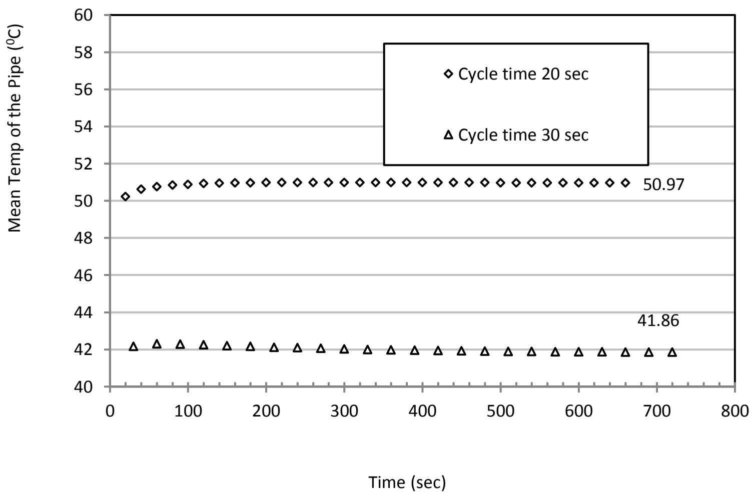

Figure 23. 20 sec vs 30 sec cycle time for alternative 5

As a result, it was found that alternative – 5 and 30 secs/cycle cooling time for the existing mould material is the most ideal for higher quality plastic end-product. If the temperature of the plastic pipe 50.97 ºC is acceptable such as in the existing plastic production, the cycle time could be 20 secs. It means, it is possible to decrease the cooling process time around 35 percentage.

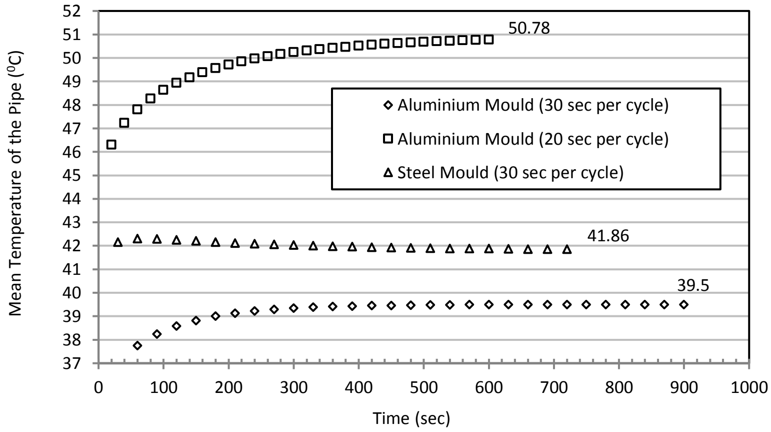

Figure 24. Aluminium (AL6061) and steel mould for alternative 5

After the ultimate geometry and duration was determined, analyses were carried out for aluminium material, which is lighter and has a much higher heat transfer coefficient. According to analyses realised for the AL6061 alloy, the average temperature of the pipe after reaching the die equilibrium is 2.36 °C lower than the steel die as seen in Figure 24. The pipe mean temperature in the steel mould is 41.86 °C, while it is 39.5 °C in the aluminium mould. In conclusion, it was found that the best cooling is possible with aluminium (AL6061) mould having reduced mass (alternative – 5) with 30 seconds per cycle cooling. So, the weight of the existing mould 86.57 kg is decreased to 16.22 kg with aluminium reduced-mass mould.

The lighter aluminium mould reaches the equilibrium in a shorter period and reduces the pipe temperature to a lower level in 30 seconds per cycle. In addition, the temperature distributions on the cooled pipe are better than the other solutions (Figure 25, Figure 26). As it can be seen from the figures, the temperature distributions of the aluminium and steel moulds at the beginning of the cycle and after the steady state condition are quite different. It is understood that moulds and pipes are heated as the cycle increases.

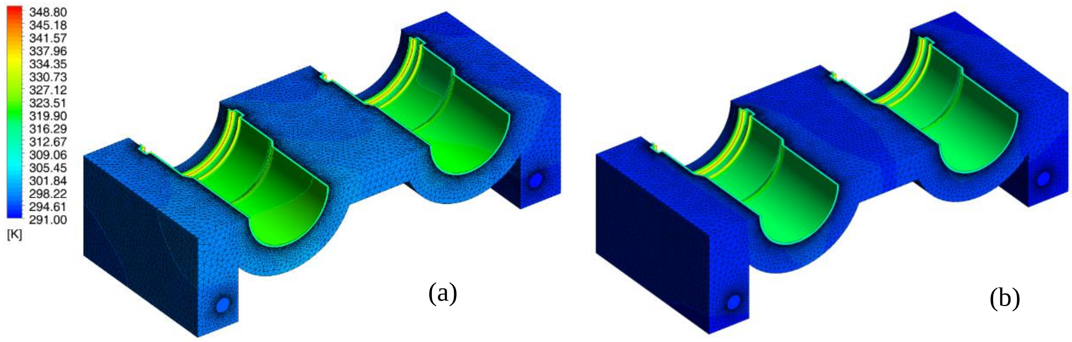

Figure 25. Aluminium mould temperature distribution, 30 sec/cycle (a) 30 cycles, (b) 2 cycles

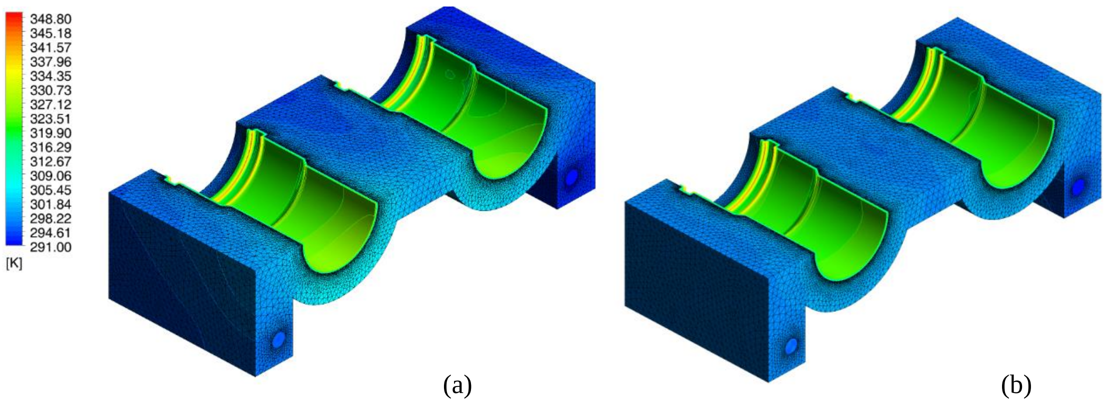

Figure 26. Steel mould temperature distribution, 30 sec/cycle (a) 24 cycles, (b) 2 cycles

In Figure 27, the temperature distributions on the cross-section taken from a plane parallel to the pipe axis are given in steady state condition for the steel and aluminium moulds. As seen from the temperature distributions, a more homogeneous temperature distribution and lower temperature are obtained in the aluminium mould.

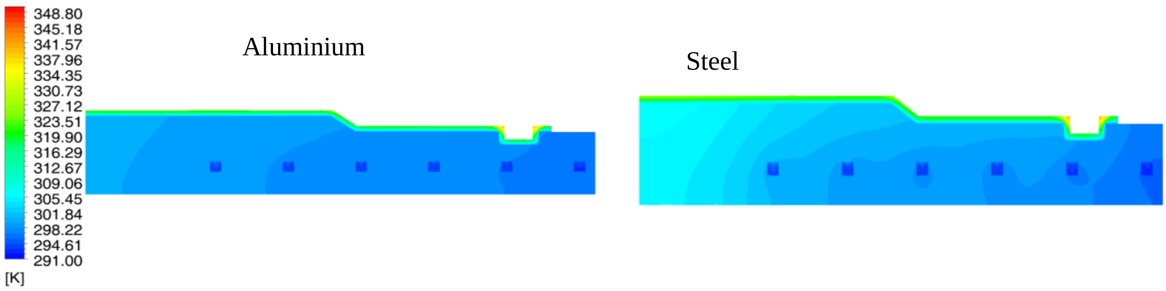

Figure 27. The temperature distribution on the cross-section of the aluminium and steel mould in steady state.

It is possible to say that the pipe temperature changes at a temperature lower than 0.1 ^{o}C after approx. 12-13 cycles in aluminium material and alternative – 5 geometry, hence it can be assumed that it is in steady state condition. Since each cycle is 30 seconds, it is necessary to wait at least 6 minutes before a pipe can be used in serial production. After this period, the mould is now in equilibrium and the pipe placed at 364.15 K can be cooled at a temperature of which 4.47 ^{o}C lower than the existing channel's (existing channel's temp is 43.97 ^{o}C- suggested channel's temp is 39.5 ^{o}C) after 30 seconds in each cycle. The following figures show how a pipe in steady state of mould cools down for 30 seconds from a 364.15 K temperature (Figure 28, Figure 29).

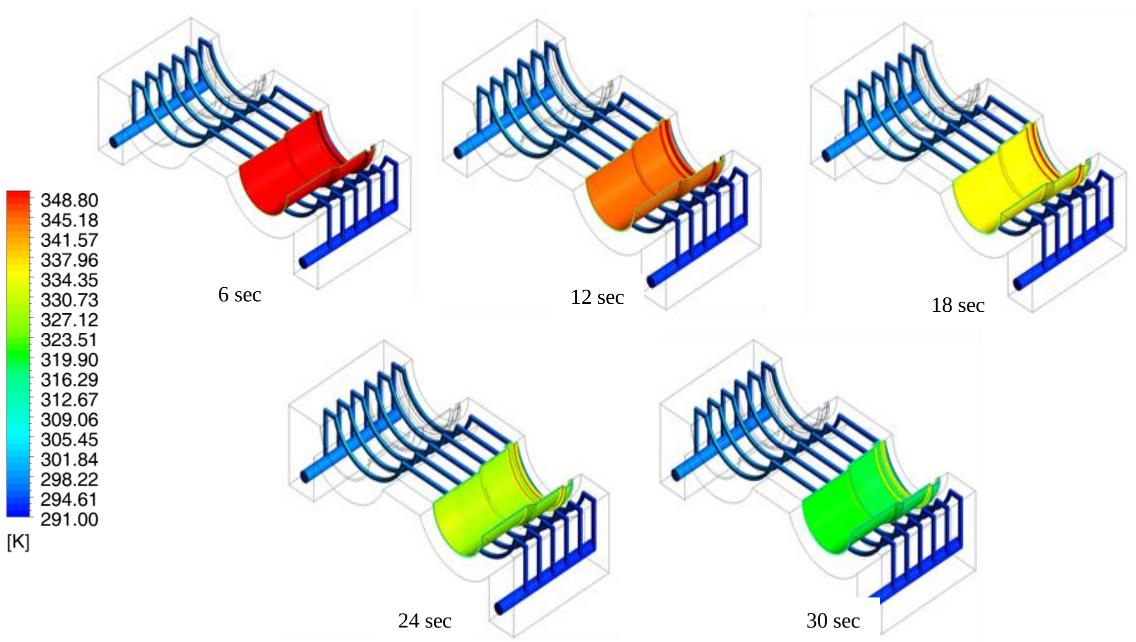

Figure 28. The temperature distribution change of the channel and pipe in time after 12 cycles (6 minute) which is the mould's steady state condition.

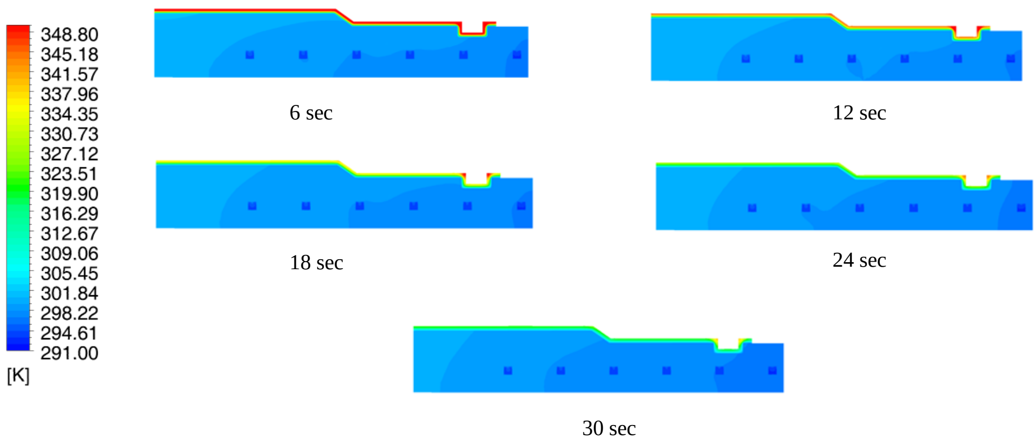

Figure 29. The temperature distribution change of the cross-section in time after 12 cycles (6 minute) which is the mould's steady state condition.

CONCLUSION

The most important parameter that affects the total processing time in the pipe forming (muff forming) process, which is one of the important steps in the extrusion process, is the cooling time affecting the production quality. It is desirable that the pipe temperature is as homogeneous and low as possible after cooling process. In that way, a stable shape can be obtained in the pipe-end and the distortions due to temperature differences can be prevented.

With this study, a lighter and easier-to-manufacture mould which makes cooling more efficient was developed. After all the analyses made, it is understood that a mould from aluminium material and with alternative – 5 geometry which is containing square channels following the curves of the pipe circumferences is the most optimal.

In conclusion, although cooling process time and mean temperature of the pipe-end were 30 secs and 43.9 ºC respectively for the existing cooling die, these values were determined as 30 secs and 39.5 ºC for the optimised aluminium die. If the temperature of the cooled pipe is taken as the same with the existing cooling process, the cooling time decreases to 20 secs for the suggested die. The weight of the die was reduced from 86.57 kg to 16.22 kg.

NOMECLATURE

3D	Three-Dimensional
ANN	Artificial Neural Network
ATS	Anti-Shrinkage System
CAD	Computer Aided Engineering
CAS	Computer Aided Synthesis
CFD	Computational Fluid Dynamics
DN	Diameter Nominal
DOE	Design of Experiments
FEA	Finite Element Analysis
HCL	Hydrogen Chloride
JIT-DM	Just in Time Decision Making
PE	Polyethylene
PP	Polypropylene
PVC	Polyvinyl Chloride
RHCM	Rapid Heat Cycle Moulding
SBCE	Set-Based Concurrent Engineering
c_p	specific heat [J/kgK]
E	energy [J/kg]
$\vec{F}$	external body forces, momentum source [N/m^3]
$\vec{g}$	gravity vector [m/s^2]
h	enthalpy [J/kg]
I	unit tensor

$\vec{J}_j$	diffusion flux of j species [mole/m^{2}s]
k_{eff}	effective thermal conductivity [W/mK]
p	Pressure [Pa]
Re	Reynolds number
S_m	mass source term [kg/m^3 s]
S_h	heat sources [W/m^3]
T	Temperature [K]
ρ	density [kg/m^3]
μ	dynamic viscosity [Pa s]
$\bar{\bar{\tau}}$	stress tensor
$\vec{v}$	velocity vector [m/s]

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