

# Investigation on Cooling Channel in Hot Press Forming Through Numerical Simulation



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## ABSTRACT

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Quenching process in the hot press forming process was important in ensuring the sheet metal undergoing effective rapid cooling simultaneously with the stamping process. Efficient quenching will harden the sheet metal by transforming its microstructure from austenite to martensite. Studies on quenching process through numerical simulation was highly favorable in obtaining optimized parameters for manufacturing-used. This can avoid waste production during the HPF process and reduce the time consumption from real life experimental work. In this paper, the process and the details of the hot press forming process was reviewed based on previous reference journal. The parameters varied in the paper such as forming temperature and the blank holding force was explained in term of its effect on the process. The effect of cooling channel design parameter in the hot press forming die such as the cooling duct diameter, the shape and the surface distance were also discussed and overviewed. Lastly, the research has concluded the more biggest size diameter with circular shape and nearest to the location of cooling channel was proposed to the best cooling rate and the most economical.

### Keywords:

Ultrahigh Strength Steel; Hot Press Forming; Cooling Channel Design Parameters; ANSYS Fluent

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## 1. Overview on the Quenching of Hot Press Forming

Hot press forming (HPF) also known as press hardening or hot stamping is a new technology which formed the ultrahigh strength steel (UHSS) as a blank material (950 °C) into complex shapes and quenched in the dies which have cooling channel [1-2]. During the quenching of hot press forming process, the cooling rate of cooling channel play an important role in order to harden the hot blank

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material in the dies. Proper and adequate quenching will help the blank to obtain the required strength properties due to the microstructural change from austenite into martensite [3-4]. Nowadays, numerical simulation has become indispensable to make a feasible quick calculation and prediction in early stage of test run production [5]. In the past decade, several studies conducted forming and quenching parts in hot forming through numerical simulation procedure [6]. ANSYS Fluent was used to perform numerical simulation for cooling effect in quenching to obtain the durability of a dies and the microstructure properties of blank material. If the heat transfers from the blank material to the dies did not discharge efficiently through the cooling channel design, the wear resistance of the dies could be reduced and hence affected the quality of blank material [7]. However, thermal behavior of quenching in hot press forming was still difficult to be observed through experimentally and involved high cost due to the need of using high technology equipment for temperature detection such as thermograph cameras [8]. Hence, the thermal behavior of cooling channel performance in the quenching condition through numerical simulation was seen to be in potential and must be further investigated in the hot press forming process.

Past studies have shown that the blank holder force (BHF) and velocity of cooling water of processing parameters effects on the dies with BR1500HS material (UHSS) through OriginPro8 software of both numerical simulation and experiment were studied. As a result of the numerical studied, increased of the pressure holding time has decreased the cooling performance in dies but increased the water velocity of cooling channel which leads to improvement on the quality of final stamping part [9]. The cooling channel parameters as maximum temperature, average temperature, temperature uniformity, pressure drop between inlet and outlet, and maximum velocity in cooling channel for several cooling channel design especially straight cooling and conformal cooling channel (longitudinal, transversal, and parallel) in hot press forming die was evaluated [10]. Subsequently, the larger diameter of the cooling channel, the closer to the die surface, the better the cooling effect but could affect the strength of the dies and the final stamping part [11]. Straight cooling channels in the dies can absorb heat effectively and cool down faster but the temperature and rate of heat transfer were not uniform [12]. As observed the distribution of the cooling temperatures in the HPF die which the heat dissipation in the convex area is slower than in concave area. Therefore, the temperature of the upper die cools down slower than the lower die [13].

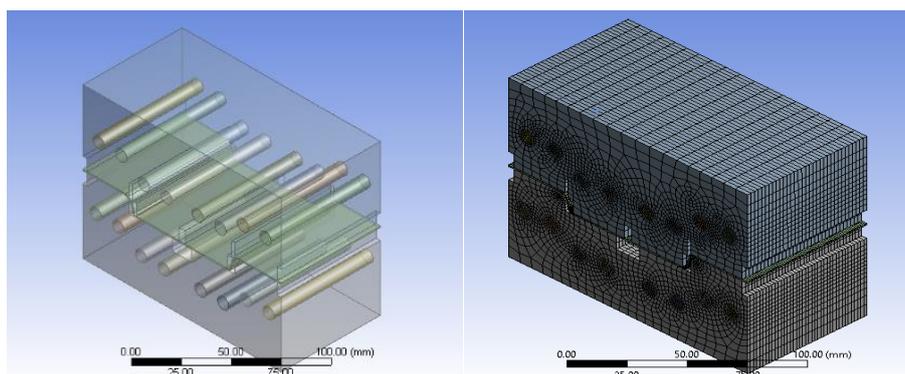
Consequently, a calculation criterion for the straight cooling channel design parameter selection such as diameter, number of channel, location to the die surface and the die strength was proposed [14]. Temperature distribution representing hardness of the simulated final stamping parts on near optimised cooling channel in the HPF die by CFD analyses [15]. The method for designing the cooling channel parameters were based on the shape factor, energy balance, and evaluation criterion model was evaluated [16]. Another new technology, slice dies to evaluate the cooling performance in hot press forming in numerically and experimentally was introduced [17]. Thus, tool split and a connection rules of 2D sections for arrangement of the number of cooling channel and the diameter through energy balance principles was proposed [18]. An experimental numerical procedure to determine time temperature transformation diagrams (TTT) through continuous cooling transformation diagrams (CCT) with residual stress for cooling simulation was implemented [19]. The temperature change due to a mixture of hot fluid and cold fluid at the pipeline can cause a loss of energy, pressure drop and affect the fluid flow rate in experimentally was investigated [20]. Thus, the effect of blank initial temperature towards the springback defect in HPF was investigated [21].

However, numerical studies of straight cooling channels design parameters in the dies enhancement in term of temperature and rate of heat transfer were relatively fewer as compared to the numerous experimental studies. Although experimental studies have provided a good understanding of fluid flow physics in enhancing the cooling rate, phase transformation of

microstructure but some of the important fluid flow characteristics such as water velocity or mass flow rate through the cooling channel design parameters in the dies and heat transfer between the die surface with the blank material through trial and error method were very costly and time consuming to obtain experimentally [22]. Therefore, the aim of this paper was to develop a Computational Fluid Dynamics (CFD) model for improving the understanding on the fluid flow characteristics in the aspect of cooling channel design parameters enhancement. In the present paper, a geometric model which consists of the cooling channel design parameters with a composition of hot press forming dies with the blank material were created by SolidWorks. The diaphragm motion of the quenching in the hot press forming process was realized by a k-epsilon method. Temperature solution and cooling rate were introduced into the fluid flow from different design parameter of cooling channel. The cooling rate and temperature result are numerically predicted as the result of the Computational Fluid Dynamic (CFD) model. The cooling rate and temperature distribution results obtained by using location closer to the die surface of 14 mm although same size diameter of cooling channel of 8 mm is validated against the experimental results.

## 2. Methodology

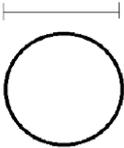
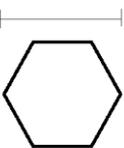
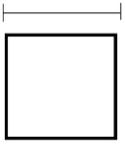
The designed was exactly based on the original profile of Lai [23] as Figure 1. Numerical simulation for various cooling channel design through ANSYS Fluent in Universiti Tun Hussein Onn Malaysia was analyze.



**Fig. 1.** Detail drawing about the blank material and the cooling channel of the HPF die model

The straight cooling channel was generated outside surface in the HPF die with hollow passageway of water flow inside the die [24]. The channel of cooling design parameters was designed with the shape of circular, hexagon and rectangular illustrated in Table 1 was studied.

**Table 1**  
 The dimension and design parameters of the cooling channel

Shape of cooling design	Circular	Hexagon	Rectangular
Side length	8 mm 	8 mm 	8 mm 
Number of sides	0	6	4
Perimeter contacted, mm <sup>2</sup>	25.133 mm	24.000 mm	32.000 mm

## 2.1 Experiment Test Observation

A model of hot press forming dies was conducted through experimentally in Universiti Malaysia Pahang (UMP), Malaysia under Malaysian Ministry of Education grant, as shown in Figure 2.



**Fig. 2.** Experimental setup at Universiti Malaysia Pahang

During the experiment test, the boron steel 22MnB5 with the dimension of 140 mm × 70 mm × 1 mm was used as the blank material in this research studied [25]. Initially, the blank material was heated up to 950 °C by using oven furnace. Then the blank material was transfer to the hydraulic forming with the force of 100 KPa. The water temperature of 5 °C with the velocity of 5 m/s in the cooling channel with size diameter of 8 mm and the distance to die surface of 14 mm in the hot stamping dies with temperature of 27 °C was applied. A hat shape of final stamping part was obtained during quenching process at time of 7 seconds. The temperature at the center point of the final stamping part was measure by using the infrared thermometer. Table 2 illustrated about the process parameters setting and experimental test results.

**Table 2**

Hot press forming parameters

Hot Press Forming Parameters	
Initial temperature of die	27 °C
Temperature of blank material after heating	950 °C
Temperature of blank material before stamping	850 °C
Temperature of final stamping part (Centre Point)	120 °C
Furnace temperature	950 °C
Duration of heating	100 s
Punching force	100 KPa/980 N
Duration of quenching	7 s
Temperature of water in cooling channels	5 °C
Velocity of water flow in cooling channel	5 m/s

## 2.2 Numerical Governing Equations for Fluid Dynamics

For the stated objectives, a commercial Computational Fluids Dynamic (CFD) software ANSYS Fluent version 19, was used to simulate the quenching of hot press forming process. The pressure-based solver is utilized to obtain the solution of transient in pressure and velocity flow 3D model with K-epsilon of viscous model. Based on the principle of conservation of mass and momentum, the numerical governing equations are derived from the continuity equation. The governing equations being solved in the water flow of cooling channel in the dies with energy equations:

### 2.2.1 K – epsilon model (k - ε model)

Turbulence modelling is the computational procedure to solve and analyse the fluid flow introducing some approximations in the governing differential equations so that required solution is obtained approximately consuming feasible computational memory and time. The standard k - ε model is a model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). The model transport equation for k is derived from the exact equation, while the model transport equation for ε was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart by Eq. (1):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (1)$$

### 2.2.2 Energy equations

The energy equation used to move the fluid flow in the cooling channel by Eq. (2). It can be shown that the rate of doing work by a force exerted on a moving body is equal to the product of the force and the component of velocity in the direction of the force.

$$\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + p)) = \nabla\{k_{eff} \nabla T - \sum_j h_j \vec{J}_j + (\bar{\tau}_{eff} \vec{v})\} + S_h \quad (2)$$

### 2.2.3 Rate of change

The rate of changes was defined as the changes in the values divided by the changes of the time. The calculation of the cooling rate based on the cooling temperature by using Eq. (3).

$$\text{Rate of changes} = \left| \frac{\text{Final temp.} - \text{Initial temp.}}{\text{Change in time}} \right| \quad (3)$$

## 2.3 Numerical Simulation Analysis

The numerical simulation takes the hat shape model as the object for established the virtual model of composition included the blank material, the upper die, the lower die and the cooling channel which detail information has illustrated in Table 3.

**Table 3**  
Different type of design parameters for the cooling channel

Die Model	Diameter of cooling channel, D (mm)	Distance between the surface of hot press forming die to the center of cooling channel, S (mm)	Shape of cooling channel
1	6	10	Circular
2	6	14	Circular
3	6	18	Circular
4	8	10	Circular
5	8	14	Circular
6	8	18	Circular
7	10	10	Circular
8	10	14	Circular
9	10	18	Circular
10	8	14	Hexagonal
11	8	14	Square

The grid independence study was conducted for ensure the reliability and fidelity of the simulation procedure correlative with the verification process [26]. At mesh generation of numerical simulation, the nodes of 48048 and the elements of 37675 for the cooling channel in hot press forming dies of the simulation procedure was studied. The grid independence study with the element quality of 0.9876 and aspect ratio of 1.138 in mesh metrics for mesh evaluation was obtained. Lastly, the mesh structure [27] and the geometry mesh was discussed [28].

### 2.3.1 Boundary conditions

At inlet, velocity inlet condition was implemented where water enters with 278 K temperature in correspondent velocity. At outlet, pressure outlet condition was given with zero-gauge pressure for all simulation. So, mass weighted average of pressure at inlet gives pressure drop in this system. Simulations were run at a constant heat flux of 50 W/m<sup>2</sup>K at the wall of the cooling channel. Navier-Stokes equation coupled with energy equation and K epsilon model two equations were modelled and solved.

### 2.3.2 Solution method and convergence criteria

Transient state, gravity independent (since model is horizontal) analysis was done. Semi Implicit Pressure Linked Equations (SIMPLE) was used as pressure velocity coupling method for this simulation. Second order upwinding was selected for continuity, momentum and energy to check the variables inside each cell. Under relaxation factor and other parameters were set to default value.

## 3. Results and Discussions

In this numerical study, the water velocity across the cooling channel in the HPF die is kept constant at 5 m/s. The size dimension of the upper die and the lower die was 140 mm X 70 mm X 54 mm respectively with the object of the hat shape model.

### 3.1 Validation of Computation Results

Numerical simulation results obtained through the pressure velocity of numerical approaches, temperature distribution and cooling rate at the center point of the blank material were compared

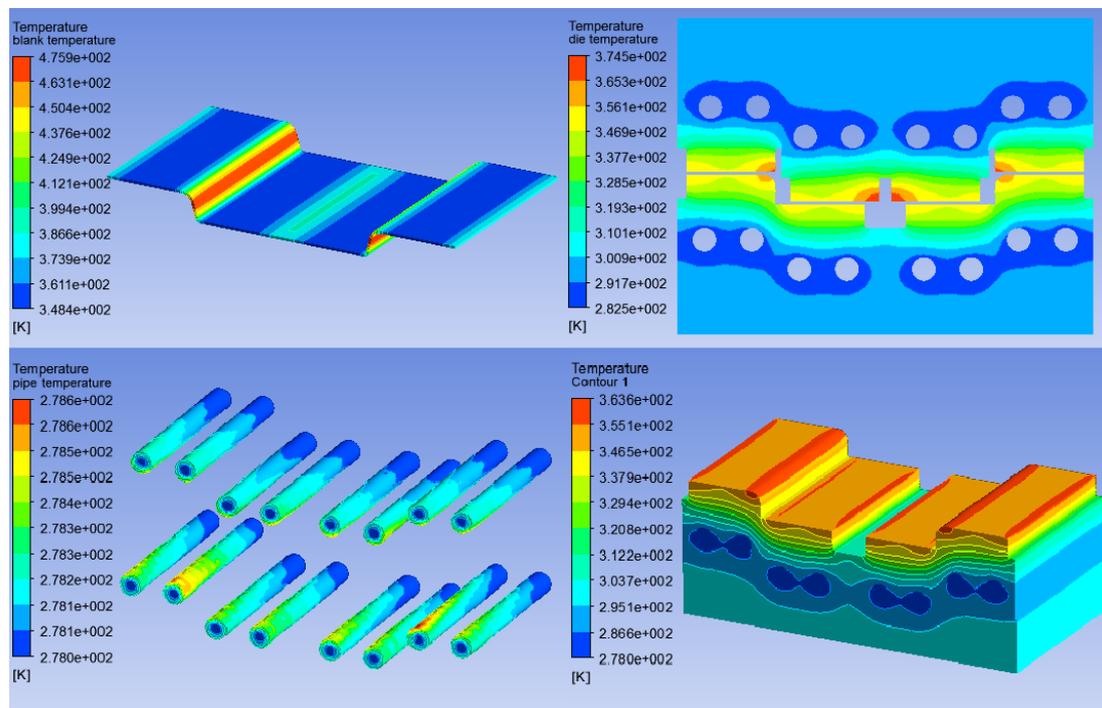
with the experimental data collected. As shown in Table 4, both experimental data and CFD results show similar graph trend indicating validation on the temperature distribution and cooling rate at the center point of the blank. These trends of results validated the numerical simulation model with the experimental work design. Apart from that the percentage difference of 4.6% which was below then the 10% mark indicates the applicability of the numerical simulation model. The optimization on the cooling which was the next phase of the study can be done efficiently since the validation had been done successfully.

**Table 4**  
 Comparison result between experimental test and numerical simulation

Result	Experimental Test Results	Numerical Simulation	Percentage Difference
The temperature at the blank material	120 °C	114.428 °C	4.6%

### 3.2 Temperature Distribution

During numerical simulation studied, the diameter of cooling channel was 8 mm, distance cooling channel to the blank material and distance from cooling to die surface is 14 mm, and the inlet velocity of the cooling channel was 5 m /s. Such process parameters are chosen because they are often used in experimental test of hot press forming for new blank material. From the temperature distribution results during quenched with cooling channel design parameter using ANSYS Fluent V19 as in Figure 3.



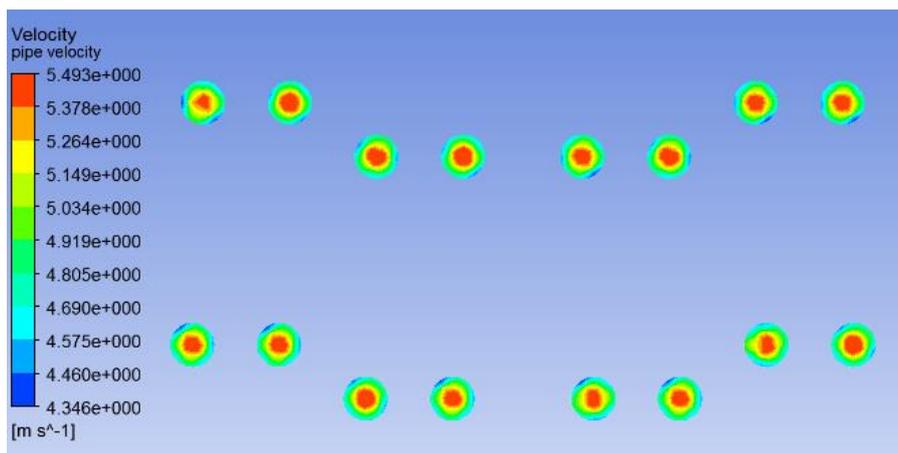
**Fig. 3.** Contour of the temperature distribution in hot press forming process

The result shown in Figure 3, explains the contour of heat transfer temperature distribution in the quenching of hot press forming process included the blank material, the upper die and the lower die. As observed at upper right corner in Figure 3, the maximum temperature of 475 K was indicated at the walls of blank material and was reduced to 348 K at the floor of blank material. Besides,

maximum temperature of 374 K was observed at sharp radii of the upper die and the lower die at the right upper corner in Figure 1. As observed at the lower die, maximum temperature of 364 K indicated at the surface of the die at lower right corner in Figure 1. Therefore, it has indicated that the cooling temperature has decreased greatly after cooling by the cooling channel.

### 3.3 Velocity Distribution

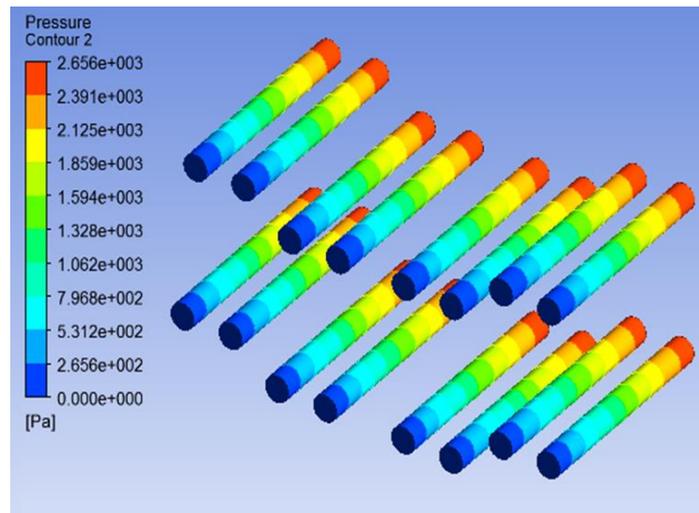
From the numerical simulation results using ANSYS Fluent V19 then obtained result as in Figure 4. The result shown in Figure 4, explains the contours of heat absorption of water velocity in the cooling channel of HPF die, the contour is shown to see how much heat is absorbed by water flow at the outlet of cooling channel in HPF die. The greatest heat in straight cooling channel is part out, because all heat absorbed the fluid will accumulate on the blank material so that the contour on the outlet of cooling channel is red color. It indicates that there has been an increased in temperature of outlet cooling channel. The maximum of water velocity at the outlet for cooling channel in the die was 5.493m/s, while the minimum of water velocity at the outlet of cooling channel was 4.346m/s. The maximum of water velocity at outlet was indicated at the center of cooling channel in the die and the minimum of water velocity at outlet was indicated at the surface of the cooling channel in the die.



**Fig. 4.** Velocity distribution of cooling channel in hot press forming through numerical simulation

### 3.4 Pressure Distribution

As observed in Figure 5, the pressure distribution of water flow in the cooling channel of HPF die. The maximum of water pressure was 2656Pa at the outlet of cooling channel and the minimum of water pressure was 265Pa at inlet of cooling channel in the HPF die. An increment of 2kPa was seen within the cooling channel. Through the observation, it was seen that the pressure had increased throughout the flow. This was due to the two regions in the pipe itself which were the entrance region and the fully developed region. Within the entrance region (located close to the inlet) of the pipe, there were decelerating phenomenon in the fluid flow, hence balanced needed to be achieved through flow inertia, shear forces and pressure. When the flow had fully developed in the pipe, the shear forces and the pressure gradient balanced each other while flowing with constant velocity profile. The increasing of pressure indicated a fully developed flow region at the outlet part of the pipe.



**Fig. 5.** Pressure distribution of cooling channel in hot press forming through numerical simulation

### 3.5 The Different Cooling Channel Design Parameters Study

Numerical simulation studied about the blank material quenched with the different cooling design parameters of the circular shape cooling channel are given in Table 5 which corresponded to the temperature characteristics. As observed in the Table 5, the blank material temperature at the center point was 386.599 °C at the size diameter of cooling channel was 6 mm while the blank material temperature was 385.153 °C at the size diameter of cooling channel was 10 mm although the location between the cooling channel and the die surface of 10 mm. Besides, the blank material temperature at the center point was 386.599 °C at the location between the cooling channel and the die surface was 10 mm while the blank material temperature was 388.031 °C at the location between the cooling channel and the die surface was 18 mm although the size diameter of cooling channel was 6 mm. It has indicated that the larger diameter of cooling channel and the closer to the die surface, the better cooling rate of 105.407 °C. Table 5 shown that the cooling effect was poor at the temperature 104.996 °C when the location cooling channel was far away from the die surface of 18 mm although the cooling channel was same diameter of 6 mm.

**Table 5**

The temperature and cooling rate of the blank material with cooling channel design parameter through numerical simulation results

		Size diameter of cooling channel, D (mm)		
		6	8	10
Location between cooling channel with surface of HPF die, S (mm)	10	386.599 (°C)	386.196 (°C)	385.153 (°C)
		105.200 (°C)	105.258 (°C)	105.407 (°C)
	14	387.646 (°C)	387.428 (°C)	387.27 (°C)
		105.050 (°C)	105.082 (°C)	105.104 (°C)
	18	388.031 (°C)	388.017 (°C)	387.912 (°C)
		104.996 (°C)	104.998 (°C)	105.013 (°C)

Remarks

- The temperature of the blank material
- The cooling rate of the blank material

### 3.6 The Shape of the Cooling Design Study

Three different shape of the cooling channel designs are investigated in this study. The cooling channel shape configurations for this numerical simulation illustrated in Table 6. As observed in the Table 6, the blank material temperature at the center point was 383.8 °C at the cooling channel was circular shape while the blank material temperature was 383.92 °C at the cooling channel was square shape although the cooling channel was same diameter of 8 mm and closer to die surface of 14 mm. Besides, the cooling rate at the blank material was 105.6 °C at the cooling channel was circular shape although closer to the die surface was 14 mm with the same size diameter of cooling channel while the cooling rate of the blank material was 105.582 °C was the square shape of the cooling channel although the closer to the die surface was 14 mm with the same size diameter of cooling channel was 8 mm. It has indicated that the circular shape of cooling channel, the better cooling rate of 105.6 °C. Table 6 shown that the cooling rate does not give much effect for the shape of cooling channel design in the HPF die.

**Table 6**  
Shape of cooling channel with temperature distribution through numerical simulation

	Cooling Channel Design		
	Circular	Hexagonal	Square
The temperature of the blank material	383.8 (°C)	383.01 (°C)	383.92 (°C)
The cooling rate of the blank material	105.6 (°C)	105.71 (°C)	105.582 (°C)

## 4. Conclusions

Research concluded with a comprehensive reflection on the heat transfer phenomenon within the HPF die through the application of ANSYS Fluent. The cooling rate and temperature distribution throughout the hot press forming process was successfully discussed and evaluated. Several other conclusions determined were listed as follows:

- I. The temperature, velocity and pressure distribution were successfully determined and evaluated within this study with references to the cooling channel.
- II. Diameter size of cooling channel along with the location of cooling channel was studied and the determination of optimum diameter size and best location were through the temperature distributed on the blank material and cooling rate value.
- III. Optimum diameter size of cooling channel determined within this study was 10 mm and the best location for the cooling channel was 10mm from the surface of HPF die due to the lowest temperature and highest cooling rate achieved.
- IV. Studies on the shape of cooling channel determined the effect of hexagonal and square cooling channel to the cooling rate and performance of the HPF die in reference to the circular. Circular piping was seen to possessed the best cooling rate and the most economical and applicable shape out of the three.

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