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# Numerical Study of Coolant Flow Phenomena and Heat Transfer at the Cutting-Edge of Twist Drill

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**Abstract:** Cutting tool coolant channels play a pivotal role in machining processes, facilitating the efficient supply of cooling agents to high-stress areas and effective heat dissipation. Achieving optimal cooling at the tool's cutting-edge is essential for enhancing production processes. Experimental investigations into tribological stress analysis can be limited in accessing complex tool–workpiece contact zones, prompting the use of numerical modelling to explore fluid dynamics and tribology. In this study, the coolant flow dynamics and heat dissipation in drilling operations were comprehensively investigated through computational fluid dynamics (CFD) modelling. Four twist drill models with varying coolant channel arrangements were studied: standard model drill, standard model drill with notch, profile model drill, and profile model drill with notch. Two distinct approaches are applied to the coolant inlet to assess the impact of operating conditions on fluid flow and heat dissipation at the cutting-edge. The findings emphasize that cutting-edge zones have insufficient coolant supply, particularly in modified drill models such as the standard model drill with notch and profile model drills with and without notch. Moreover, enhanced coolant supply at the cutting-edge is achieved under high-pressure inlet conditions. The standard model drill with a notch exhibited exceptional performance in reducing thermal load, facilitating efficient coolant escape to the flute for improved heat dissipation at the cutting-edge. Despite challenges like dead zones in profile models, the standard-with-notch model yielded the most promising results. Further analyses under constant pressure conditions at 40 and 60 bar exhibited enhanced fluid flow rates, particularly at the cutting-edge, leading to improved heat dissipation. The temperature distribution along the cutting-edge and outer corner demonstrated a decrease as the pressure increased. This study underscores the critical role of both coolant channel design and inlet pressure in optimizing coolant flow dynamics and heat transfer during drilling operations. The findings provide valuable insights for designing and enhancing coolant systems in machining processes, emphasizing the significance of not only coolant channel geometry but also inlet pressure for effective heat dissipation and enhanced tool performance.

**Keywords:** drilling; CFD; coolant; heat dissipation; internal cooling channel design

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## 1. Introduction

In the realm of mechanical manufacturing processes, drilling stands out as a pivotal metal shaping operation. However, the involvement of various secondary phenomena in drilling operations renders the entire process costly, particularly when aiming for high-quality outcomes and process reliability [1,2]. During drilling operation, both tool and workpiece are exposed to a very high temperature, resulting from evolving friction and shear force at the tool and workpiece interface [3–5]. This extreme thermal load reduces the strength of the tool material and accelerates tool abrasive and adhesive wear, which affects machining accuracy and productivity, and diminishes tool life and the surface quality of

the workpiece [6,7]. In this context, the supply of internal coolant plays the most important role in improving the process efficiency and extending tool life. However, the intricacies of drilling, where the cutting operation occurs inside the workpiece, pose a significant challenge in ensuring an adequate supply of coolant at the tip of the tool [8–10]. This is particularly crucial for efficient heat dissipation at the cutting-edge area. Additionally, the removal of chips increases the complexity of the drilling operation, subjecting the tool to high torsional loads because of the spiral flutes and less favourable cooling conditions [2]. Thus, a comprehensive understanding of the mechanisms contributing to tool wear and surface integrity in the drilling process is really important.

In analysing the tribological stress on the drill, comprehensive thermodynamic properties of the tool and cutting fluid, body of the tool, counter-body of the chip, optimizing the ideal coolant, location and structure of the coolant channel, corresponding exit position on the flank face, and coolant flow rate and pressure must be meticulously taken into account [11]. The implementation of appropriate cooling technology can reduce tool wear, prolong tool life, and improve surface quality as well as overall sustainability of the production system [12,13].

During the cutting process with a twist drill, the supply of cutting fluid to the cutting zone is facilitated through internal cooling channels. However, complexity arises as the exit points of these cooling channels are situated on the flank face, creating a challenge in delivering adequate coolant to the cutting zone and leading to an indirect cooling process [7]. Moreover, the complex behaviours of centrifugal and Coriolis forces come about due to increased angular velocities and the curvature of the spiral channels, thereby influencing the turbulent flow of the coolant. In addition to that, the gap between the tool and workpiece is very small, requiring the velocity of the coolant to be twice as large as the maximum cutting speed to effectively fill this confined space [14]. To ensure the proper cooling effect and decrease the thermal load, various design modifications can be applied. By changing the location, diameter, and geometry of the cooling channels, a higher lubricant flow rate and thermal convection can be obtained. However, it is noteworthy that experimental investigations into tribological stress analysis are often constrained and, at times, rendered impossible due to the inaccessibility of the complex cutting zone.

Arrazola et al. [15] provided a comprehensive overview of the state-of-the-art complex machining operations within metal cutting processes, highlighting research gaps that require immediate attention for improved outcomes. While numerous investigations have been conducted on metal cutting operations, with a predominant focus on milling and turning, the attention dedicated to the drilling process is notably limited, despite it being one of the most prevalent machining operations [16]. This is possibly due to the difficulties in accessing and analysing the complex cutting zone [17].

Among all drilling operations, almost 75% of jobs are performed using twist drills [18]. The process of developing an effective drilling tool has always been difficult compared to other cutting processes. Numerous thermo-mechanical aspects such as cutting force, heat transfer, wear resistance, torsional and axial stability, and chip evacuation capability must be taken into account when studying drilling operations. Consequently, cutting parameters in drilling operations are often limited to heat dissipation capacity during machining. Furthermore, tool geometry, feed, bore hole quality, lubrication, and cutting materials have significant influence in prolonging tool life and improving the surface quality of the workpiece [16,19].

Kumar and Deivanathan [20] have presented a comprehensive overview of the control factors and mechanisms in both conventional and deep hole drilling processes. Their work emphasizes that the effectiveness of the deep hole drilling depends on torsional rigidity of tool, efficient coolant supply, and proper chip removal. These processes are highly influenced by the cutting speed, application of cutting fluid, and depth of hole.

In addressing these challenges, numerical modelling can be useful for investigating fluid dynamics and tribology at the interface of tool and workpiece. Due to the advancement of computational technology, numerical prediction, and optimization of tools, the efficiency of cutting process has been substantially increased. The computational fluid dynamics

(CFD) modelling technique has proven to be very effective and convenient for studying real fluid flow and heat transfer in the complex cutting zone, especially when experimental testing and analysis is impractical [21].

Continuum-based CFD simulations can be modelled using two main approaches: Eulerian and Lagrangian. In the Eulerian approach, phases are considered as interpenetrating continua and modelled using different conservation equations and coupled with source terms. Hence, necessary constitutive equations must be applied to describe the interaction between the solid and fluid phases, accounting for solid stress contributions. On the other hand, in the Lagrangian approach, the fluid phase is assumed to be a continuum and solved by using time-averaged Navier–Stokes equations and external forces are taken into account as they act directly on each and every particle by solving the equations of motion.

Many researchers have numerically studied the effects of coolants on drills by comparing the results of cutting temperatures, tool wear, bore quality, thrust force, and drilling torque [22,23]. The most critical aspect of the cooling process is the flow of the cutting fluid, with its primary objectives being heat dissipation and the removal of chips from the cutting zone. In many of these investigations, the finite element method (FEM) approach is commonly applied, which is good for studying solid-state behaviour; however, it is less suitable when analysing coolant flows, particularly when turbulence occurs [2,24]. In contrast, the application of computational fluid dynamics (CFD) in machining processes remains relatively limited. Only a handful of studies have delved into modelling the cutting process, encompassing the intricate interactions between the coolant and chip formation. This represents a challenging frontier in multiphysics modelling within the domain of machining.

Fallenstein and Aurich [25] conducted a study on the internal cooling of carbide drills using a CFD simulation. In their predicted results the authors found that heat transfer depends on the cutting fluid flow rate and the exit position of the cooling channels. In a related study, Beer et al. [7] employed a CFD-based simulation to investigate the distribution of coolant lubricant in internally cooled carbide drills. The authors introduced a methodology aimed at enhancing wear resistance and coolant efficiency through a modified flank face geometry. The predicted results demonstrated detailed information of the cooling fluid flow, and consequently, heat dissipation at the tool–workpiece interface subjected to high thermal loads. They also found that a modified groove on the flank face resulted in a better lubricant supply, consequently extending tool life by up to 50%.

Biermann and Oezkaya [11] investigated the flow distribution and coolant pressure variations based on the arrangements of the internal cooling channels and optimized these arrangements using CFD. Their analysis indicated that conventional fluid channel arrangements inadequately supplied cutting-edges with coolant. In contrast, the modification of cooling channels proved to be more effective, reducing surface wear and enhancing tool performance by approximately 36%. In another CFD investigation, Kao et al. [26] characterized the mist flow structure for minimum-quantity-lubrication (MQL) drilling. The study involved the selection of two different channel geometries—circular and triangular shapes. The results revealed that the flow structure concentrated close to the drill centre in the case of circular-shaped channels, whereas it concentrated in the vicinity of the three vertices in triangular-shaped channels.

From the literature review it is evident that CFD is an efficient tool to provide better insight into cutting fluid flow and its distribution over the complex drill cutting zone, chip removal, and heat transfer on the surface. These studies have proved that CFD is the most suitable tool for studying fluid flow dynamics and tribology when metrological methods are limited in application, especially in drilling operations where the tool–workpiece interface and behaviour of coolants are not visible [27].

In the broader context of machining processes, tool optimization is one of the most important aspects for ensuring process efficiency [28]. CFD simulations offer a pathway to optimize tool design and identify effective internal cutting fluid channels. However, most of the studies reported in the literature investigating drilling operations are found to be insufficient

when it comes in comprehensively addressing coolant flow phenomena and heat transfer at the cutting-edge covering all aspects of the drilling process. Furthermore, the literature review highlights that while researchers have explored various coolant channel arrangements, the design modifications have been somewhat limited, often focusing on circular or triangular shapes. This limitation raises the need for more comprehensive design optimization studies, particularly for dissipating excess thermal load at the cutting-edge in drilling operations.

The recognition of improved heat dissipation at the cutting-edge with the presence of a notch at the flank face, connected to the coolant channel exit, highlights the significance of coolant channel design in enhancing fluid flow. With this in mind, the current study aims to elucidate the influence of coolant channel design on fluid flow at the cutting-edge area, and thereby, heat dissipation.

This research investigates four distinct drill models, each characterized by different arrangements of coolant channels, under varying operating conditions. Each model, detailed in the subsequent sections, possesses a unique combination of shapes and sizes for the coolant channels. The four models under examination are named as follows: standard model drill, standard model drill with notch, profile model drill, and profile model drill with notch. The CFD approach is employed for analysing the coolant flow phenomena and heat transfer at the cutting-edge of twist drills, designed for deep hole drilling operations. The impact of the coolant channel design, pressure difference on the flow dynamics, and heat transfer at the cutting-edge area are investigated comprehensively.

## 2. Geometry of the Drill Models

Figure 1 illustrates the four distinct drill models employed to investigate the coolant flow phenomena. The reference drill model is the standard model, characterized by a circular arrangement of coolant channels. The other three models have modifications to the cross-sectional shape, size, and exit of the coolant channels. In comparison to the standard model, the profile model has a triangular shape with an elliptical corner of the coolant channel (Figure 1c,d), which increases the overall diameter of the channel. Two additional models, standard with notch (Figure 1b) and profile with notch (Figure 1d), introduce a notch at the exit of the coolant channel. The presence of the notch at the exit increases the exit area, and thus, is expected to improve heat dissipation by providing better fluid flow at the cutting-edge region. These four different drill models aim to reveal the optimal performance of the twist drills in improving thermal load dissipation at the cutting-edge and thereby improving both tool life and product quality.

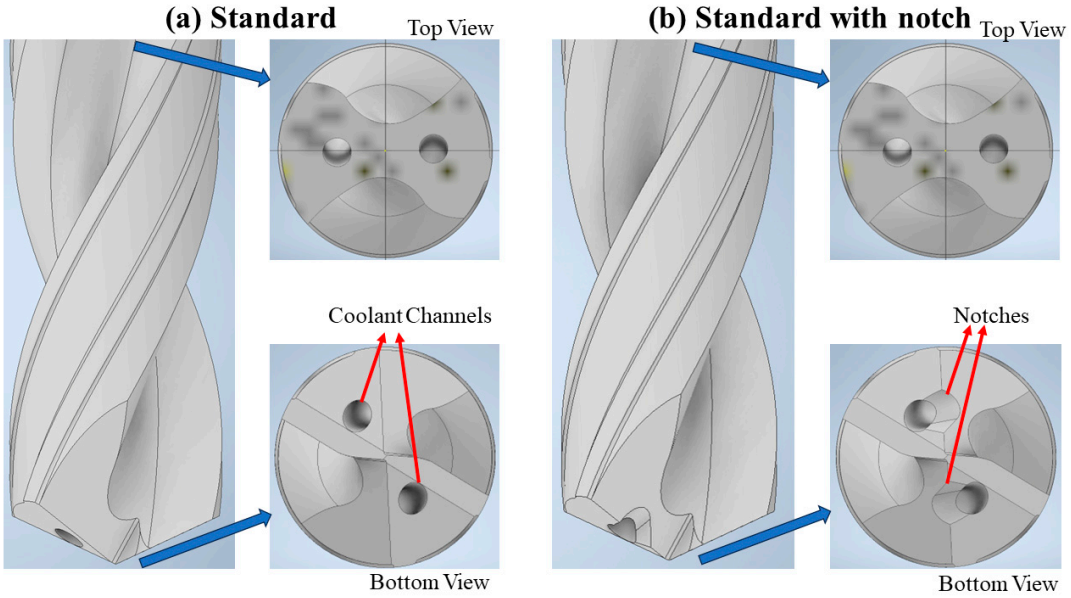



**Figure 1.** *Cont.*

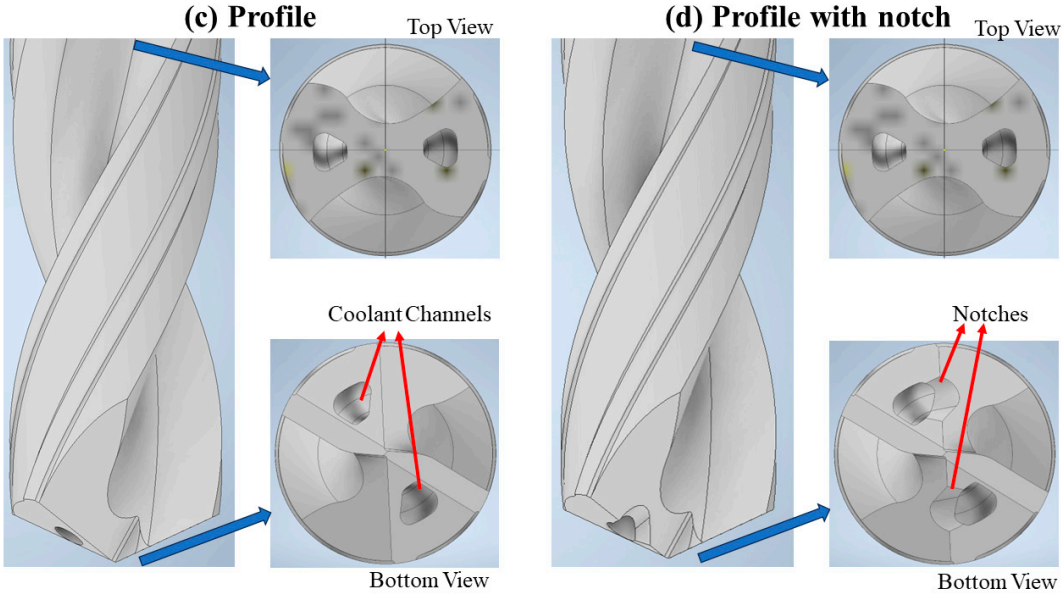



**Figure 1.** Geometries of 4 different drill models studied.

## 3. CFD Model

The physical aspects of fluid flow are ruled by three main principles: the conservation of mass, Newton's second law, and conservation of energy [21]. These basic principles are expressed mathematically in the form of partial differential equations. In this study, a three-dimensional CFD model is developed, solving the energy equation along with the mass conservation and momentum equations. The entire process is assumed to be nonreactive non-isothermal single-phase flow.

### *3.1. Single-Phase Flow Governing Equations*

For a single-phase flow, the equations of mass conservation, momentum, and energy can be written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left( \rho \vec{v} \right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left( \rho \vec{v} \right) + \nabla \cdot \left( \rho \vec{v} \vec{v} \right) = -\nabla \mathrm{P} + \nabla \bar{\bar{\tau}} + \rho \vec{g} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \left( \rho \vec{v} C_p T \right) = \nabla \cdot (k \nabla T) \tag{3}$$

where $\rho$ is the density (kg/m$^3$), $v$ is the superficial fluid velocity vector (m/s), $\bar{\bar{\tau}}$ is the stress tensor, $\rho \vec{g}$ is the gravitational body force, and $\nabla$P is the pressure gradient (Pa). In the energy equation, $h$ is the enthalpy (kJ/kg), $\nabla T$ is the temperature gradient (°C), and $C_p$ is the specific heat capacity (kJ/kg.K). The stress tensor can be formulated as Equation (4), where $\mu$ is molecular viscosity and $I$ is the unit tensor. The second term on the right-hand side defines the effect of volume dilation.

$$\bar{\bar{\tau}} = \mu \left[ \left( \nabla \vec{u} + \nabla \vec{u}^{\tau} \right) - \frac{2}{3} \nabla \vec{u} I \right] \tag{4}$$

### *3.2. Turbulence Modelling*

Turbulence is another important factor to consider in modelling cooling lubricant flow. The Reynolds-averaged Navier–Stokes (RANS) equations are often applied to describe fluid flow in a turbulent regime [7]. However, an additional transport equation is required to quantify the turbulence which must be incorporated with the RANS equations. For this purpose, the $k$-$\varepsilon$ turbulence model is applied in this study, where $k$ represents turbulent

kinetic energy and energy dissipation is defined by $\varepsilon$ [29]. This turbulence model has been applied widely in various industrial applications. In this $k$-$\varepsilon$ turbulence model, two transport equations are solved to estimate the turbulent eddy viscosity ($\mu_t$), as per Equation (5).

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

### 3.3. Research Methodology

Figure 2 represents the geometry and the fluid model of one of the analysed twist drills. To focus on the coolant flow near the cutting-edge area, only a small section of the drill (10 mm of length) is modelled. The governing equations are solved in a given three-dimensional geometry using the finite volume method and commercial CFD software AVLFire 2017 is used for the simulations. The pressure–velocity coupling and correction is adopted in the CFD model using the SIMPLE algorithm. The second-order upwind scheme is used for the discretization of the convective terms.

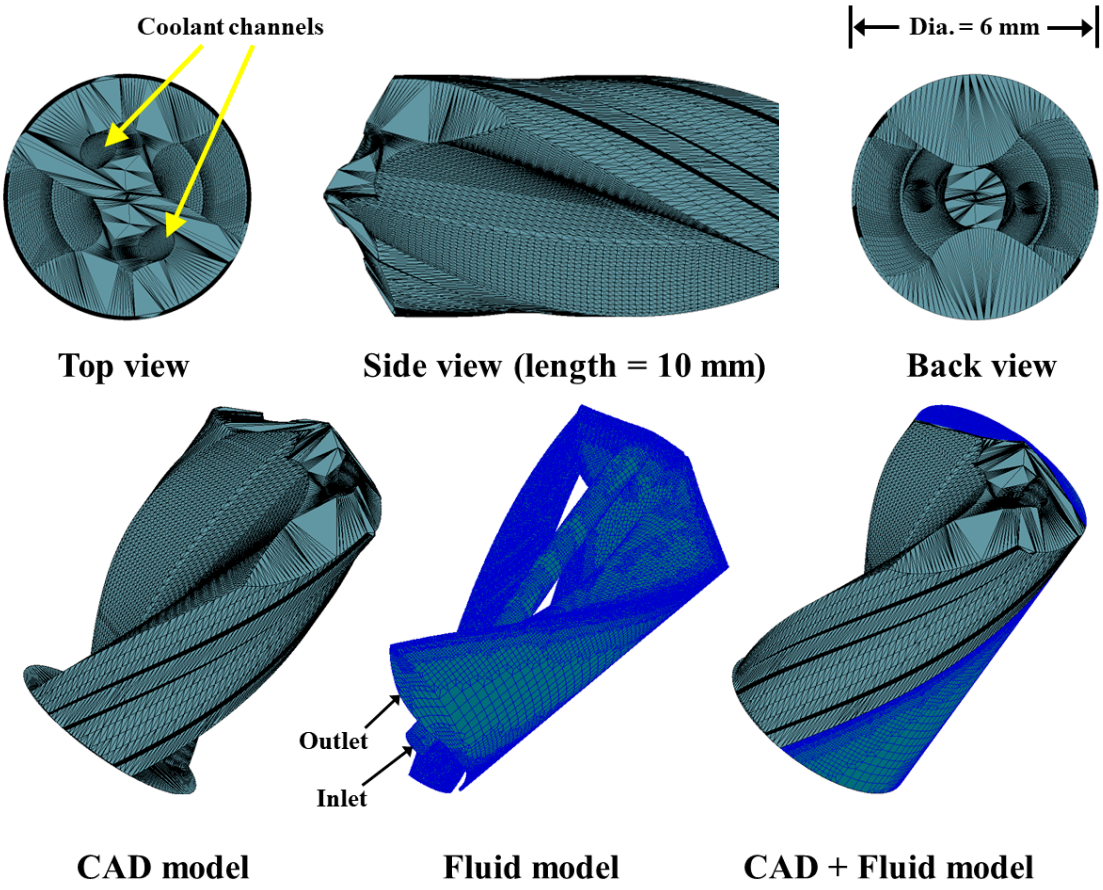



**Figure 2.** Model geometry (interpretation of CAD and fluid model).

The fluid flow is analysed for four types of drills. These drills are the same in diameter (6 mm); however, they are different regarding the shape of the coolant channels (standard and profile) and their exits. For every simulation, the inlet boundary condition is set to the volume flow rate and the outlet is set to the pressure boundary condition. The rotation of the fluid is introduced in the CFD model by applying the moving reference frames (MRFs) approach and the rotational speed is set to 2000 rpm. The applied boundary conditions and number of elements of each model are listed in Tables 1 and 2, respectively. For analysing heat transfer, an approximate temperature of 450 °C, as usually occurs in practice, found from the literature, and suggested by industry (Sutton Tools), is set for the cutting-edge area and the cooling agent is supplied at a temperature of 27 °C.

**Table 1.** Boundary conditions.

| Boundary Conditions | | |
|---|---|---|
| **Fluid** | | **Water** |
| Inlet flow rate | | 5.5 lt/min |
| Coolant channel diameter | Standard | 0.8 mm |
| | Profile | 1.0 mm (approx.) |
| Rotation | | 2000 rpm |
| Turbulence model | | k-ε |
| Run mode | | steady |
| Solver duration | | 3000 s |

**Table 2.** Number of mesh elements.

| Drill Models | Number of Cells |
|---|---|
| Standard model | 962,696 |
| Standard model with notch | 962,277 |
| Profile model | 988,536 |
| Profile model with notch | 969,643 |

## 4. Results and Discussion

The primary objective of this study is to explore the influence of coolant channel arrangements and inlet pressure differences on the coolant flow pattern at the cutting-edge area, with a concurrent focus on reducing thermal load. Numerous numerical investigations are conducted under various operating conditions to comprehensively address this objective. As depicted earlier, four types of twist drills are employed for this investigation (Figure 1), with the standard drill (without a notch) serving as the reference for performance comparison. Initially, investigations are conducted using a coolant flow rate of 5.5 litres per minute (lt/min) for each drill model. Subsequently, the study is expanded by replacing the constant flow rate with a constant pressure at the inlet.

Figure 3 presents the velocity profiles at the flank face and cutting-edge area for all drill models at the constant flow rate of 5.5 lt/min at the inlet. To assess the performance of the coolant channel arrangements with respect to coolant flow behaviour, the resulting streamlines and velocity profiles near the drill's surface are examined. The velocity profiles reveal distinct characteristics among the drill models. The standard model drill exhibits the highest coolant exit velocity of approximately 90 m/s. In contrast, the flow velocity for the standard model drill with a notch is comparatively lower, ranging between 75 and 80 m/s. The profile model drill and the profile-with-notch model drill exhibit significantly lower coolant flow velocities, ranging from 50 to 65 m/s, compared to the standard models. However, the profile model drills showcase a relatively even coolant flow distribution across the borehole area.

Despite this, all drill models exhibit a significant drop in coolant flow velocity at the cutting-edge area, reaching very low velocities, almost 0 m/s in some parts, referred to as a dead zone, indicating an 80–100% drop in coolant flow velocity from the exit bore area to the cutting-edge. This suggests insufficient cooling agent supply to these areas. Remarkably, the dead zone area is notably higher in both profile models compared to the standard model, despite having a relatively uniform flow velocity at the flank face and borehole ground, as observed from the CFD results.

Under the same initial condition of 5.5 lt/min, the pressure differences between the coolant channel inlet and outlet were analysed and are presented in Figure 4, which illustrates that the pressure difference is lower in the profile-shaped drill models compared

to the standard drill models. In other words, under the same operating conditions, the pressure of the coolant upon exiting the channel decreases as the diameter of the coolant channel increases. Differences are also evident when a notch is employed at the exit of the coolant channels, as the pressure decreases for both the standard and profile models. This observation emphasizes the influence of the coolant channel design, with implications for the pressure characteristics within the system.

The highest inlet pressure, reaching 40 bar, is observed in the standard drill model (without a notch), explaining the corresponding higher coolant flow velocity at the borehole area. Conversely, the profile model drill with a notch exhibits the lowest inlet pressure, approaching 13 bar, approximately one-third of the pressure observed in the standard model drill without a notch. In contrast, both drills, standard model with a notch and the profile model without a notch, demonstrate relatively similar pressure difference profiles, approximately 22 bar and 19 bar, respectively, at a flow rate of 5.5 lt/min. These observations highlight the influence of drill geometry and notch presence on the pressure characteristics within the system.

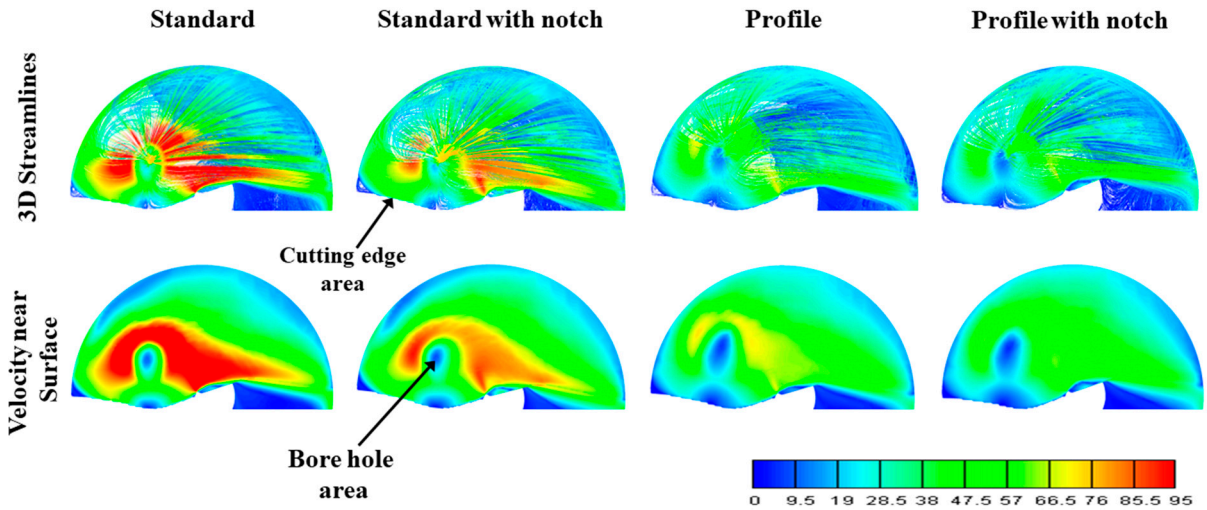



**Figure 3.** Velocity distribution profile for the given drill models at flow rate of 5.5 lt/min. Note: the colour legend is in m/s.

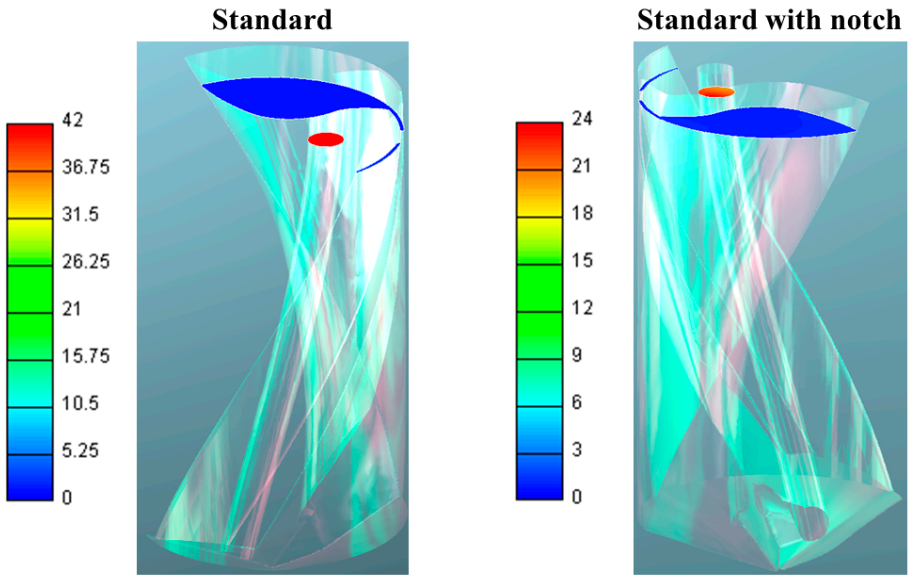



**Figure 4.** *Cont.*

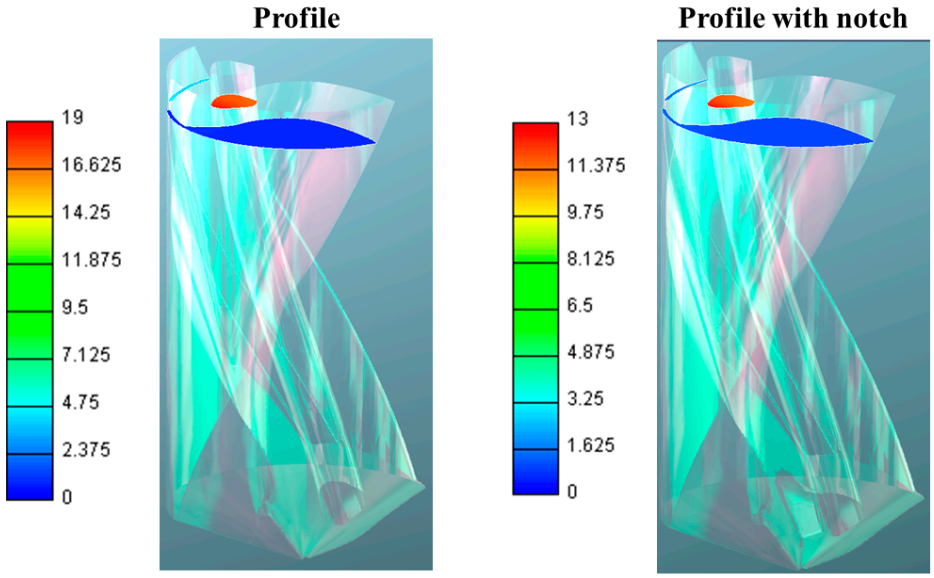



**Figure 4.** Pressure difference between inlet and outlet for different drill models at constant flow rate of 5.5 lt/min. The red spot in each image represents coolant fluid pressure in the internal cooling channel, and the blue-coloured region represents coolant fluid pressure on the external drill cutting periphery. Note: the colour legend is in bar.

Figure 5 illustrates the distribution of fluid temperature at the cutting-edge area for different drill models. The cooling agent flow absorbs a certain amount of heat generated during the cutting process in the immediate proximity of the cutting zone, resulting in local temperature variations. The figure reveals that the entire surface of the cutting-edge area experiences some degree of thermal load, irrespective of the coolant channel arrangements. However, differences in heat absorption and variations in local fluid temperature distribution become apparent as the arrangement of the coolant channels changes.

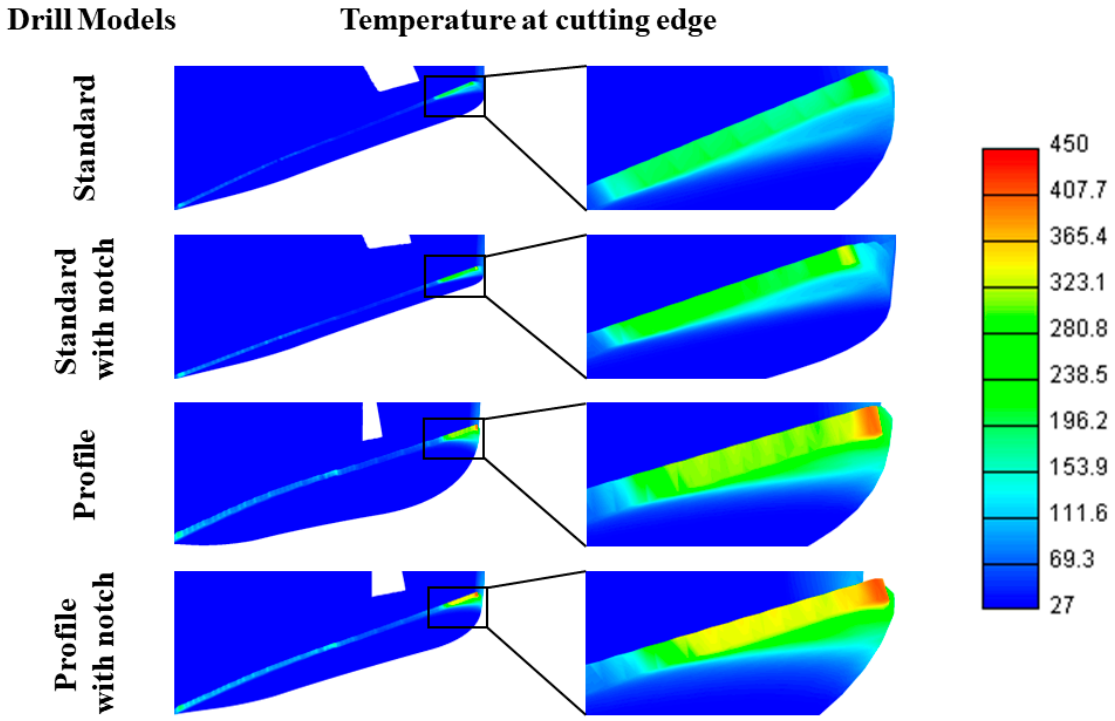



**Figure 5.** Fluid temperature distribution at the cutting-edge at constant flow rate of 5.5 lt/min. Note: the colour legend is in °C.

Numerical observations further indicate that the temperature is higher at the outer radius of the modified drill models. Notably, the standard model drill without a notch demonstrates effective heat dissipation, maintaining an average surface temperature of the cutting-edge area at around 196 °C, the lowest among all models. In contrast, the cutting-edge surface of the profile model drill with a notch experiences notably high thermal stress, resulting in an average fluid temperature of about 350 °C in the vicinity of the cutting zone.

The temperature distribution over the cutting-edge surface can be explained by the analysing the fluid velocity profile shown in Figure 3. The standard model drill exhibits a higher fluid flow rate at the cutting-edge area and a relatively smaller dead zone. This configuration enables the cooling agent to reach much closer to the cutting region, actively dissipating heat, and thereby, reducing thermal stress on the cutting-edges. Consequently, the standard model drill without a notch achieves a lower local fluid temperature distribution over the cutting-edge area. The temperature distribution on the surface of the cutting-edge in the standard model drill with notch is almost same as the standard model without notch, except for a slightly higher temperature at the outer edge of the drill, which, in fact, explains the presence of the notch and its effect on the fluid flow.

However, in the case of the profile model drills, despite achieving a homogeneous fluid distribution around the borehole area, the fluid flow at the cutting-edge is insufficient. The lack of coolant motion results in slow heat transfer, causing the cutting-edge area to undergo very high thermal stress. This observation emphasizes the impact of the fluid velocity profile on the temperature distribution.

The examination of fluid motion, pressure distribution, and temperature patterns discussed above signifies the impact of the presence of a notch at the exit of the coolant channel on fluid flow, and thereby, heat dissipation. It is evident from the analysis that the presence of a notch at the exit provides an easy escape passage for the cooling agent from the coolant channel exit to the flute. However, this excess passage limits the coolant flow reaching the complex restricted region of the cutting-edge by decreasing the flow velocity. Consequently, the cooling agent bypasses the hot cutting zone without efficiently performing its intended function. Furthermore, in the case of the profile model drills, the triangular shape with elliptical corners leads to an increased exit area of the coolant channels. As a result, this design element provides the cooling agent with additional space, allowing it to escape easily to the flute instead of engaging in heat dissipation at the cutting-edge area.

After analysing the numerical results under a constant velocity inlet condition (5.5 lt/min) it becomes apparent that the performance of the three modified drill models (the standard with notch, the profile without notch, and the profile with notch) is not better than the standard twist drill model. It is also observed that the heat dissipation at the cutting-edge area deteriorates as the diameter of the coolant channel increases, particularly in the case of the profile models. Furthermore, introducing the notch at the exit of the channels did not yield any improvements in heat dissipation.

Additional investigations on these three modified drill models are carried out whereby the inlet is adjusted with a constant pressure instead of a constant fluid flow rate, with pressures of 40 and 60 bar applied at the inlet while conducting the numerical simulations. This extended investigation aims to gain further insights into the performance of the modified drill models under varied operating conditions.

Figures 6 and 7 illustrate the differences in coolant flow velocity at the flank face and cutting-edge area for the three modified drill models under constant pressures of 40 bar and 60 bar at the inlet, respectively. From the velocity contour plots of the resulting streamlines and velocity near the surface, it is evident that the fluid flow rate has increased significantly for all models compared to that of the constant inlet flow rate (5.5 lt/min) (Figure 3). Especially at 60-bar inlet pressure, a very high coolant velocity at the cutting-edge area is observed for the standard-with-notch model drill, in particular (Figure 7).

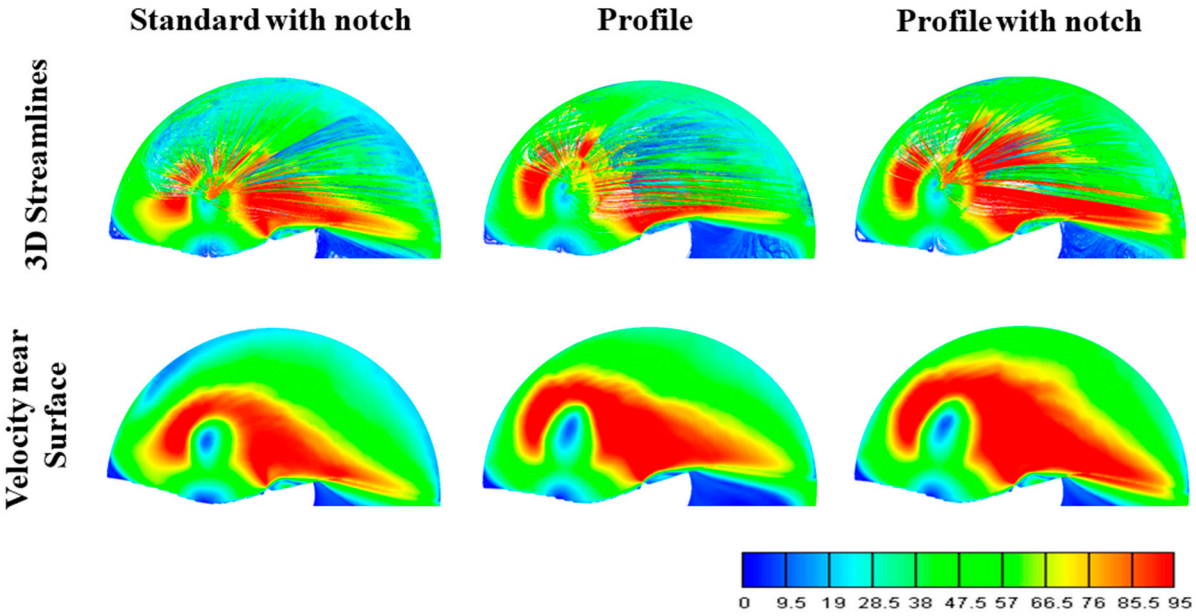



**Figure 6.** Velocity profile for standard-with-notch drill model and profile model drills (with and without notch) for constant pressure of 40 bar at inlet. Note: the colour legend is in m/s.

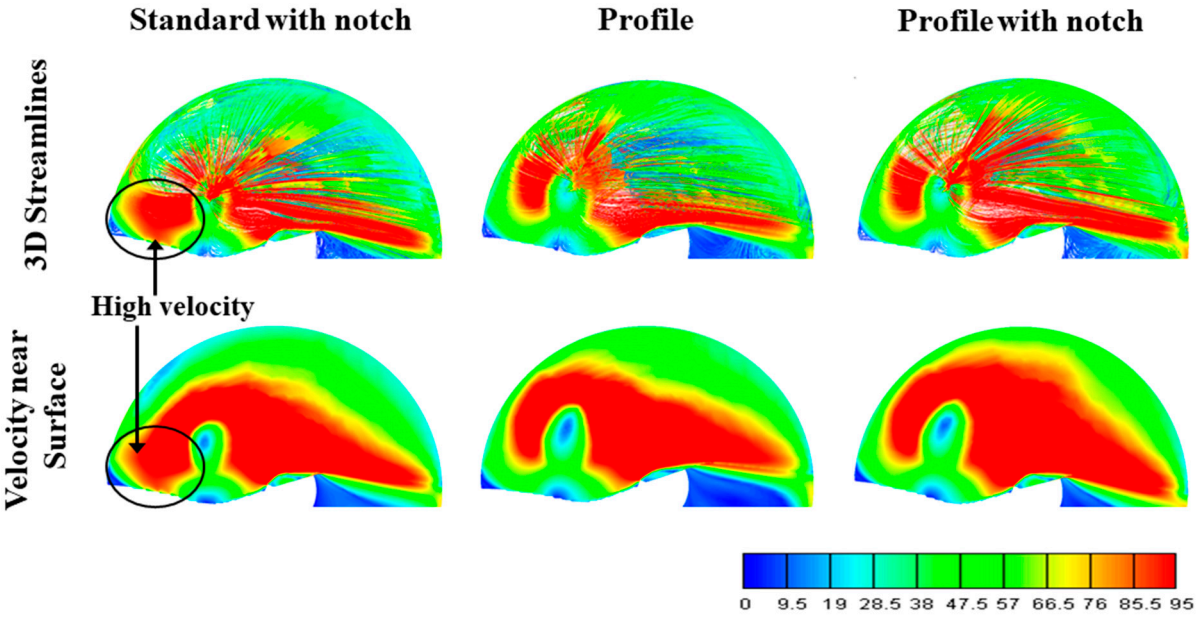



**Figure 7.** Velocity profile for standard-with-notch drill model and profile model drills (with and without notch) for constant pressure 60 bar at inlet. Note: the colour legend is in m/s.

However, some parts of the cutting-edge, and most importantly the outer corner, remain blue in colour, indicative of a dead zone with 0 m/s coolant velocity, for all models, even when the inlet pressure is 60 bar (Figure 7). While using the profile models allows for higher coolant flow velocities at the flank face and borehole ground, these modified models are not entirely effective in eliminating dead zones from the cutting-edge area. Among all three modified models, the standard-with-notch model performs the best concerning the accessibility of the coolant to the cutting-edge area. Using the standard-with-notch model, particularly at high pressure, dead zones at the cutting-edge can be reduced significantly. It is extremely challenging to eliminate such dead zones by increasing the coolant flow rate, either by adjusting pressure, fluid flow rate, or changing the coolant channel diameter. This limitation definitely impacts the heat transfer at the outer edge.

In comparison to pressure inlet and constant flow rate inlet conditions, the fluid pressure varies for each drill model (Figure 4) when the inlet condition is a constant flow rate, impacting the coolant flow at the cutting-edge area. With an increase in the diameter of the coolant channel (profile models) or the extension of the exit area due to the implementation of the notch, fluid flow is provided with an additional passage. Consequently, fluid flow does not acquire as much pressure as needed to reach the complex cutting-edge region under constant flow rate conditions. However, applying a higher pressure at the inlet changes the dynamics of the fluid flow at the bore hole and cutting-edge area.

The temperature distributions of the fluid along the cutting-edge and outer corner of all modified models under both 40 and 60 bar pressure conditions are shown in Figure 8. The primary objective of coolant flow during drilling operations is to mitigate thermal load. From Figure 8, it is evident that the entire cutting-edge is subjected to a significantly high temperature, with the very edge of the outer corner experiencing the highest temperature. Nevertheless, heat dissipation shows a notable improvement when utilizing higher pressure at the inlet.

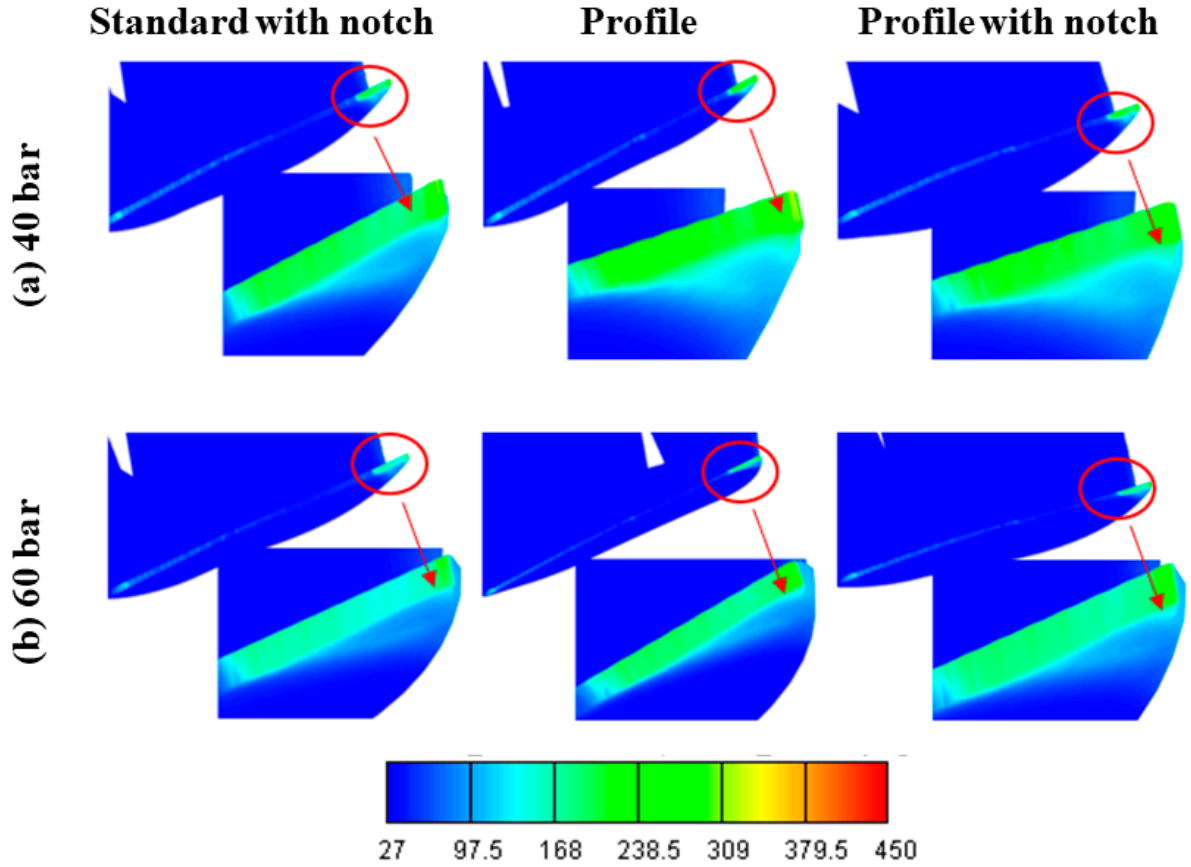



**Figure 8.** Fluid temperature distribution at the cutting-edge for three modified drill models for varying inlet pressures. Note: the colour legend is in °C.

Among the three given models, the standard-with-notch model demonstrated the most effective reduction in thermal load. This performance can be attributed to the velocity profile of the model. As shown in Figure 7, the coolant flow successfully reaches the cutting-edge area for this specific drill model, resulting in improved heat dissipation. As previously explained, fluid flow and heat transfer depend on the shape of coolant channels and their exit, among other factors. Comparing the temperature distribution for 40- and 60-bar pressures, there is a slight decrease in temperature as the pressure increases. Remarkably, at 60-bar pressure, the temperature range is relatively lower in the standard-with-notch model,

including the outer corner of the cutting-edge, where fluid flow is limited. However, at 40-bar pressure at the inlet, the very edge of the outer corner exhibits a higher temperature. Given the higher fluid flow rate near the cutting-edge area of the standard-with-notch model (Figures 6 and 7), it can be assumed that the coolant is relatively mobile at the cutting-edge area of this specific model, leading to sufficient heat transfer.

The removal of chips is a critical factor in the design and performance of drilling tools. Effective chip evacuation is essential to maintain a clear cutting zone, reduce friction, and prevent the re-cutting of chips, which can lead to increased tool wear and thermal load. In our study, the different coolant channel designs not only aimed at improving coolant flow and heat dissipation but also at facilitating efficient chip removal. The presence of notches in the modified drill models, such as the standard model drill with a notch and the profile model drill with a notch, enhanced the escape path for both coolant and chips. This design modification proved beneficial in reducing the formation of dead zones where chips could accumulate, thereby minimizing the risk of clogging and improving overall tool performance. High-pressure coolant supply further aided in flushing out chips from the cutting zone, maintaining optimal cutting conditions and extending tool life. Future designs should continue to integrate considerations for both coolant delivery and chip evacuation to enhance machining efficiency and tool durability.

In addition to the coolant channel design and pressure conditions, the rotational speed of the drill is another critical parameter that can significantly impact the flow and heat transfer characteristics. Higher rotational speeds can enhance coolant circulation due to increased centrifugal forces, potentially improving heat dissipation at the cutting-edge. However, excessive speeds might lead to turbulence and unstable flow patterns, which could negatively affect the efficiency of coolant delivery and chip evacuation. While this study did not include a parametric analysis of rotational speed, future research should investigate its effects to provide a more comprehensive understanding of coolant flow dynamics and thermal management during drilling operations.

Lastly, the typical tool material for twist drill bits is high-speed steel (HSS), known for its excellent thermal stability, hardness, and wear resistance. HSS can withstand extremely high pressures of up to 150 bar and high temperatures of up to 650 °C [30], making it ideal for demanding machining operations. In this study, the coolant channels were tested under simulations using a maximum fluid pressure of 60 bar and it was observed that the maximum temperature experienced by the tool cutting-edge was 450 °C for the profile with a notch channel design (shown in Figure 5). The combination of HSS's thermal properties and the controlled conditions used in this study ensures that the material will not degrade or lose its performance capabilities. The choice of HSS ensures the reliability and effectiveness of the tool even under the specified high-pressure and high-temperature conditions.

As per the CFD simulations, the maximum temperature experienced by the twist drill with varying coolant channel designs was 450 °C. These results were obtained by adjusting the fluid pressure and modifying the coolant channel design. Altering the drill's maximum temperature directly is not feasible without changing these process parameters. Lowering the maximum temperature would likely require increasing the coolant flow rate, improving the coolant channel efficiency, or enhancing the cooling capacity of the fluid.

For instance, increasing the inlet fluid pressure or optimizing the coolant channel geometry could improve coolant distribution and heat dissipation, thereby reducing the maximum temperature at the cutting-edge. Conversely, reducing the maximum temperature by a few percent could significantly enhance tool life and machining efficiency by minimizing thermal wear and potential thermal damage to the workpiece. Future studies could focus on systematic parametric analysis to determine the optimal combination of these parameters to achieve the desired thermal performance.

## 5. Conclusions

In this study, an extensive investigation into the coolant flow dynamics and heat dissipation in drilling operations was conducted through computational fluid dynamics

(CFD) modelling. The study encompassed four different drill models, namely, the standard model, standard model with a notch, profile model, and profile model with a notch. The main focus was on understanding the impact of coolant channel design on fluid flow at the cutting-edge area and subsequent heat dissipation.

The results of the current research draw attention to the fact that the cutting-edge zones are not sufficiently supplied with cooling lubricant when using modified drill models such as standard model drill with a notch and profile model drills with and without a notch. The investigations reveal that an improved coolant supply at the cutting-edge can be achieved using the standard model drill, thus providing comparatively better heat transfer. Thus, it can be said that among the four different drill models, the standard model drill provides better results in terms of coolant flow velocity at the cutting-edge and heat transfer. On the other hand, despite providing evenly distributed flow dynamics, the profile-shape coolant channel drill models are not efficient enough in effective heat transfer.

Furthermore, it was also observed that the standard twist drill with a notch exhibited superior performance in reducing thermal load. The presence of a notch at the exit of the coolant channel facilitated an efficient escape passage for the cooling agent to the flute, contributing to improved heat dissipation at the cutting-edge. Despite the challenges posed by dead zones in the cutting-edge area, especially in profile models, the standard-with-notch model demonstrated the most promising results.

Further analysis under constant pressure conditions at 40 and 60 bar revealed a notable enhancement in fluid flow rates, particularly at the cutting-edge, leading to improved heat dissipation. The temperature distribution along the cutting-edge and outer corner exhibited a decrease as the pressure increased.

In conclusion, this study underscores the critical role of coolant channel design and inlet pressure in optimizing coolant flow dynamics and heat transfer in drilling operations. The findings provide valuable insights for the design and improvement in coolant systems in machining processes, emphasizing the significance of not only coolant channel geometry but also the inlet pressure for effective heat dissipation and enhanced tool performance.

## 6. Future Research

Future research directions could explore additional design modifications and operating conditions to further refine the understanding of coolant behaviour in drilling operations, aiming towards more sustainable and efficient machining processes. Moreover, the research can be extended to analyse fluid flow in the vicinity of the highly stressed area by varying the fluid pressure or mass flow rate at the inlet to further improve the flow rate with the objective of reducing the dead zones as much as possible while dissipating heat. This could include studying the thermal behaviour of the solid and fluid interfaces during chip formation and the flow of the chips through the flute face and their evacuation using a cooling agent.

The primary objective of this study was to understand and establish the effect of tool coolant channel design on coolant flow phenomena and heat transfer using a simple fluid like water. Future research should extend this investigation by using industrially relevant coolants with varied physical properties such as density, viscosity, and thermal conductivity. Evaluating these properties in both experimental and simulation studies will help in obtaining results that are directly applicable to real-world machining processes. This approach will enhance the relevance and applicability of the findings, providing valuable insights for optimizing coolant systems in industrial settings.

This study primarily focused on the impact of coolant channel design and inlet pressure on flow and heat transfer characteristics. Future research should extend this investigation to include the effect of drill rotational speed. A parametric study analysing how different rotational speeds influence coolant flow patterns, chip evacuation, and thermal load could offer valuable insights. Understanding these dynamics would contribute to optimizing drilling parameters, ultimately enhancing machining efficiency and tool longevity.

Experimental and numerical studies incorporating rotational speed as a variable will be critical to developing more effective and sustainable drilling processes.

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