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Thermo-fluid Topology Optimization and Experimental Study of Conformal Cooling Channels for 3D Printed Plastic Injection Molds

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Abstract

With the advent of additive manufacturing, innovative design methods, such as network-based techniques, and structural topology optimization have been used to generate complex and highly efficient cooling systems in recent years. However, methods that incorporate coupled thermal and fluid analysis remain scarce. In this paper, a coupled thermal-fluid topology optimization algorithm is introduced for the design of conformal cooling channels. The problem is formulated based on a coupling of Navier- Stokes equations and convection-diffusion equation. The problem is solved by gradient-based optimization after analytical sensitivity derived using adjoint method. With this method, the channel position problem is replaced to a material distribution problem. The material distribution directly depends on the effect of flow resistance, heat conduction, natural and forced convection. The algorithm leads to a two-dimensional conceptual design having optimal heat transfer and balanced flow, which is further transformed into three-dimensional cooling channel design. Here, a comprehensive study is presented, starting from design, simulation, 3D printing process and experimental testing of an injection mold with conformal cooling channels in industrial production environment. A traditional mold model is provided by an industrial collaborator. To enhance the overall thermo-fluid performance of the mold and improve final product quality, a redesign of this mold core is done with conformal cooling channels inside. The final design is 3D printed in pre-alloyed tool-steel powder Maraging Steel using Truprint 3000 metal 3D printing machine. The printed core required some heat treatment and finishing processes and added features to be incorporated to make it production ready. Once all the preparation was complete, the core was tested experimentally in a multicavity injection molding machine in real industrial environment at our industrial partner's production facility. This paper describes all the steps starting from design, analysis, die 3D printing and finally ending at final experimental testing, as well as recommendations for tool designer and injection molding industry to implement additive manufacturing for their benefit. This paper is not just focused on a specific aspect such as design , simulation or manufacturing, but rather a comprehensive paper presenting a case study on implementation of topology optimization and additive manufacturing in real life industrial production scenario.

Keywords: topology optimization; conformal cooling; metal 3D printing; plastic injection molding; experimental study; additive manufacturing

1. Introduction

Additive manufacturing enables the fabrication of parts and tools of high geometric complexity, challenging traditional design guidelines of cooling systems in heat exchangers, injection molds and many more industrial heat-transfer cases. Additive manufacturing (AM) allows several innovative design approaches that intricate cooling system in mold inserts, which is conformal to the shape of plastic injected part, offering significant reduction of production cost [1]. The optimal design approach to fabricate such cooling channels is particularly a newer research area. As a particularly useful finite element analysis-based design approach, topology optimization is the replacement of a structural optimization problem with material

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distribution problem, brings in a high degree of geometric freedom for the conceptual design.

In this research work, topology optimization method is implemented in solving a real-life industrial problem. The proposed method fully combines thermal and fluid topology optimization to obtain an optimal cooling channel system in the heated design domain. Expansive studies can be found for topology optimization associated with thermal conduction [2-5]. Natural heat convection was included in [6-8]. So far, large scale three-dimensional heat sink cooled by thermal conduction and natural convection obtained from topology optimization is available for experimental tests [9, 10]. Forced convection has also been addressed by introducing surrogate material interpolation models[11-13]. On the other hand, many studies aim to find flow passages having minimized energy loss using topology optimization [14-20]. In these researches, the optimal designs are mainly derived from stokes flow[14, 15] and laminar flow [17, 18]. Topology optimization based on turbulent flow model is still a new research area, in which only a few recent studies have been conducted [19, 20].

In the thermal-fluid coupled system, thermal and fluid finite element analysis are dependent. In Koga et al.[21] and Dede's work[12, 22], velocity field of the fluid flow derived from Stokes flow model is introduced to the thermal model to determine forced convection, and the material distribution directly depends on flow resistance.

In topology optimization, two objectives associated with thermal and fluid performance are aggregated through weighing coefficients, to formulate a multi objective function. Further, this approach has been accomplished in detail, leaded an improvement of optimality[23-25]. Moreover, in these studies, the fluid model has been broadened from a Stokes flow to Laminar flow model. However, these studies only consider the heat transfer that is locally dependent on the flow field and evaluated quantitatively on the fluid-solid boundary[24]. Besides, the results occasionally represent an unbalanced flow, and make no sufficient flow rate through certain areas of a channel, thus limited and non-uniform heat transfer.

There have been other efforts in optimizing the design of conformal cooling channels[26-30]. With the potential of additive manufacturing to create wide variety of sizes and shapes with higher geometric complexity, conformal cooling channels can be implemented in the tools and dies used in plastic injection molding industry. Execution of design optimization of cooling channels in the industrial applications is addressed in some recent studies [31-36]. In addition to topology optimization, a different approach of design of experiments (DOE) has been undertaken [33, 34, 37]. Jahan et al. [38] addressed the cost reduction of additive manufacturing in such tool design cases using prototyping and finite element analysis method.

The proposed method in this paper aims at evaluating and optimizing heat transfer performance of the entire design domain with a comprehensive perspective. In this method, material distribution is directly affected by flow resistance, heat conduction, as well as natural and forced convection. Additionally, to specify the cooling uniformity demand for an injection mold, the flow balance of the cooling system is calibrated. The consequential conceptual design is transferred to a Computer-aided Design (CAD) format, and mapped to a morphological surface that is conformal to the injected part. For the fluid model, to reduce the computational cost, a laminar flow is assumed in the optimization procedure, in which the finite element model is frequently called, and the feasibility of the final three-dimensional design is verified in thermal-fluid finite element analysis using a turbulent model. Final three-dimensional designs can be exported as both 3D graphic and surface mesh formats.

2. Thermal-Fluid Topology Optimization Method

The proposed method aims at searching for the optimal topology in the design domain Ω in Fig. 1, with prescribed heat source q, inflow and outflow locations (Γ_{inflow} and $\Gamma_{outflow}$), as well as the inflow and outflow properties as velocity v, temperature T and pressure p.

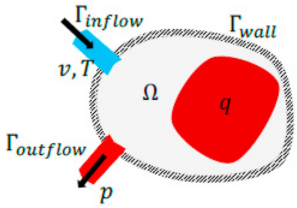

Fig. 1. Problem setting of the proposed topology optimization algorithm.

In the proposed thermal-fluid coupled problem, thermal compliance is formulated as the objective, both fluid and thermal finite element analysis are needed as constraints. The optimization problem statement is as follows:

$$\begin{aligned} &\text{find } \theta^{c*} \in \mathbb{R}^{ne} \\ &\min Q^c = \mathbf{q}^{\mathrm{T}}\mathbf{T} \\ &\text{s.t. } \begin{bmatrix} \mathbf{K} & -\mathbf{G}^{\mathrm{T}} \\ -\mathbf{G} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{0} \end{bmatrix} \\ &\mathbf{K}_{\mathbf{t}}(\mathbf{u})\mathbf{T} = \mathbf{q} \\ &\sum_{e=1}^{ne} v_e \theta_e \leq \mathrm{V} \end{aligned} \tag{1}$$

Where $\mathbf{q}$ is nodal heat flux, $\mathbf{T}$ is nodal temperature, $\mathbf{K}$ is stiffness matrix of Navier-Stokes flow, $\mathbf{G}$ is the coupling matrix, $\mathbf{u}$ is nodal velocity, p is nodal pressure, f is nodal friction force, $\mathbf{K}_t$ is stiffness matrix of heat transfer equation. v_e is the porosity of each element θ_e and V is volume fraction.

To achieve the flow balance in the system, an additional optimization problem is formulated. For this problem, resulting topology is derived from previously mentioned Eq. (1) is utilized. In the conceptual design, a section Γ_i that contains n number of flow channels is selected. Same velocity $u_1^i = \ldots\ldots = u_n^i$ is distributed on each of the pipe sections $\boldsymbol{d}_1^i = \ldots\ldots = \boldsymbol{d}_n^i$. With the new boundary conditions, a fluid topology optimization problem is formulated as follows:

$$\text{Given,} \quad \theta^{c*} \in \mathbb{R}^{ne}$$

$$u_1^i = u_2^i = \cdots u_n^i \in \{d_1^i = d_2^i = \cdots d_n^i\} \in \Gamma^i$$

$$\min Q^c = \frac{1}{2}\mathbf{u}^{\mathrm{T}}\mathbf{K}\mathbf{u} - \mathbf{f}^{\mathrm{T}}\mathbf{u}$$

$$\text{find } \theta_1^{c*} \in \Re^{ne}$$

$$\text{s.t.} \begin{bmatrix} \mathbf{K} & -\mathbf{G}^{\mathrm{T}} \\ -\mathbf{G} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{0} \end{bmatrix} \tag{2}$$

$$\mathbf{K_t}(\mathbf{u})\mathbf{T} = \mathbf{q}$$

$$\sum_{e=1}^{ne} v_e \theta_e \leq \mathrm{V}$$

Where, Q_1^c is energy dissipation of fluid flow. This procedure is designed to calibrate flow balance by optimizing the diameters of the pipe sections without affecting much of geometry configurations.

The topology of the conceptual design is presented in a Bitmap format file. To convert this to a CAD file, several procedures are carried out in Grasshopper®, which is a graphical algorithm editor tightly integrated with Rhinoceros® 3D modelling tool. In the first step, interface between solid and fluid phases is captured using *Image sampler* component, and the central lines of the pipes are found. On the basis of these central lines, *Pipe variable* component is used to create pipe geometries that fits the interface. In the next stage, the *Surface Morph* component is used to make the geometries conform to the given morphological surface. The result geometries can be volumetrically meshed, and the design can be validated through three dimensional thermal-fluid simulation. Topology optimization is solved using MMA solver, the result is obtained after 200 iterations. The finite element analysis, problem statement and sensitivity analysis are programmed as in-house MATLAB code. Detailed description of the fluid flow and heat transfer model related with this study is presented in recent publication [39].

3. Implementation in Industrial Plastic Injection Mold

In this section, the proposed method is applied to redesign an industrial plastic injection molding tool and implement an optimal conformal cooling system of in the core insert. The existing core insert is made of MoldMAX material and is traditionally machined, which is used for manufacturing containers utilized in automated pharmacy compounding system. The design of the core insert is shown in Fig. 2. The traditional mold has machined cooling system inside it with buffers to direct the coolant (water) flow in the core. Cooling of mold is very important and a crucial factor for the competitive business of plastic injection industry. Better cooling performance and lesser cooling time is of great importance to them. The topology optimization method is thereby implemented to design an optimal configuration of conformal cooling channels to improve the performance of the tooling.

For this purpose, the cylinder close to the injected part is determined as the morphological surface. Half of the cylinder surface is flattened and chosen as the design domain (length:80cm, width: 60cm). The inlet and outlet of the cooling system have a diameter of 4cm. The design of the other half of the cylinder is symmetric to the result obtained from this specific design domain. Dimensionless parameters are defined in design domain Ω_2^c, namely $u_0 = 1$, $p_0 = 0$, $T_0 = 0$, and heat source $q_0 = 0.01$ is uniformly distributed (Fig. 2(a)). A constant heat conductivity over the entire domain $k_0 = 10$ with $p_c = 0$ is also defined. On the other hand, natural convection co-efficient $h_0^1 = 0.1$ and penalty $p_n = 2$, forced convection co-efficient $h_0^2 = 10$ and penalty $p_v = 2$ are determined. These setting implies that, in this system, heat transfer is mainly affected by forced convection, which basically shows the effect of coolant water flowing inside the channels. In addition to that, flow damping force $\alpha_0 = 100$ and penalty $p_b = 0.03$ are also defined. No global gradient constraint ($\gamma_2^c = 0$) is involved in this problem. Symmetric boundary conditions are employed to the bottom side. The result of the thermal-fluid topology optimization is shown in Fig. 2(b).

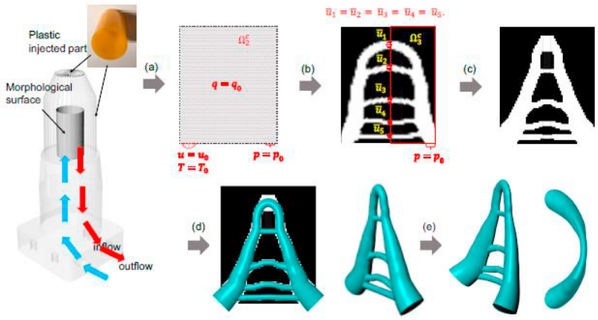

Fig. 2. Design procedure of the conformal cooling system.

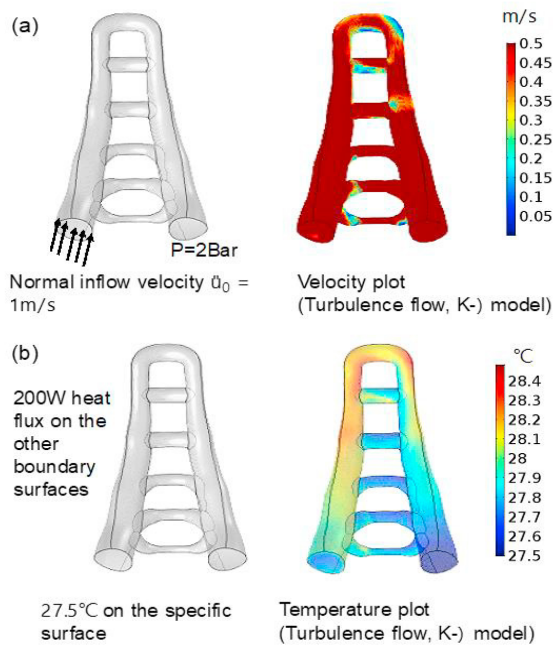

Fig. 3. Thermal-fluid coupled simulation for cooling system.

To balance the flow, same velocities are defined in the central line, and a fluid topology optimization problem is formulated in design domain Ω_3^c, that leads to the result shown in Fig. 2(c). Afterwards, the conceptual design is converted to a three-dimensional CAD format and mapped to the morphological surface shown in Fig. 2(d) and Fig. 2(e). The final design is re-meshed using Mimics 3-matic®. The simulation in COMSOL Multiphysics® shows there are sufficient flow rates for the entire channels and uniform fluid temperature under worst case scenario (Fig 3). The final design is shown in Fig.4.

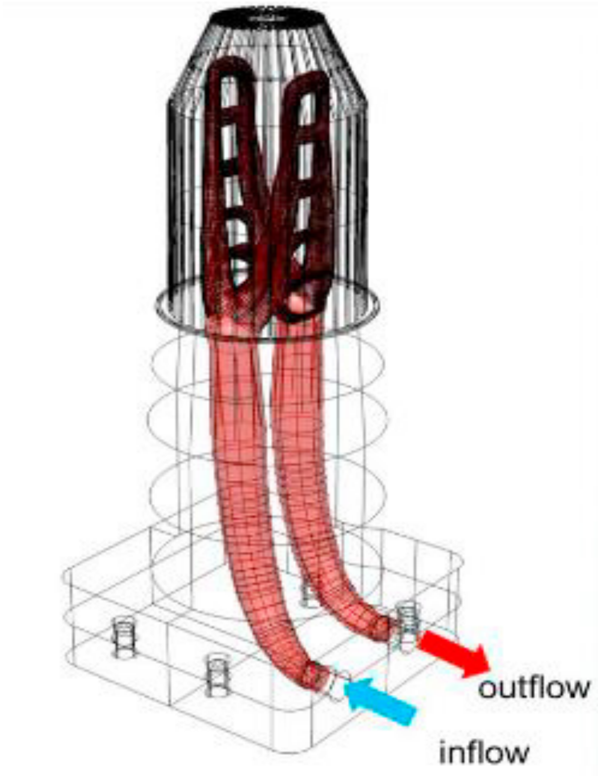

Fig. 4. Final optimized design.

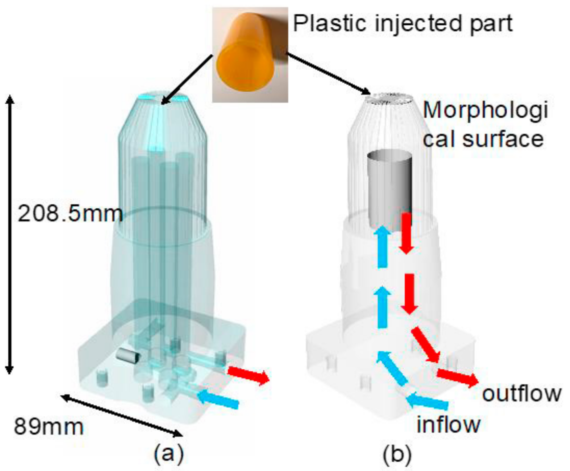

Fig. 5. Traditional core design with buffer induced cooling system

The cooling channels are marked in red colour. Notably, in final designs, thin shells are created in order to provide additional thickness for post process machining. Final three-dimensional designs can be exported as both solid model format such as (*.x_t*, *.stp*, *.iges* etc.), as well as surface mesh model format (.stl, .vrml, .ply etc.) which brings in convenience to the manufacture department to run the tool path for final fitting.

The design of the core is inspired from an existing model of industrial core as mentioned previously. The main design is unchanged, only the coolant flow system is redesigned in the optimized 3D printed core. In the original traditional core, the coolant flow is supported by buffer system, as shown in Fig. 5.

4. Metal Printing of Redesigned Core

The redesigned core with conformal cooling channel system is printed at the location of industrial collaborator TRUMPF GmbH+ Co.(Ditzingen, Germany). The core insert design is exported in solid CAD model format and used to build in TruPrint 3000 production system. At first, the part is placed in a virtual build cylinder (Fig. 6) and a support structure is added.

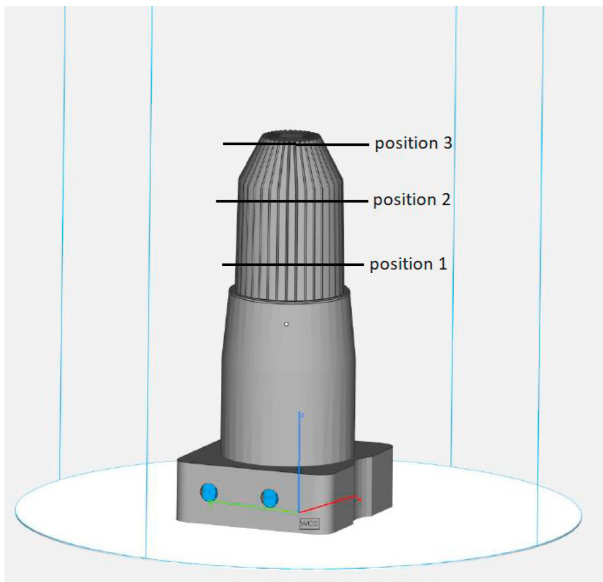

Fig. 6. CAM software picture with support structure in a virtual build cylinder.

The part is printed with pre-alloyed tool steel powder Maraging Steel and further heat treatment and surface finishing operations are applied on it. Further details of the build process are beyond the scope of discussion in this article.

5. Experimental Testing

The 3D printed or additively manufactured (AM) core insert is experimentally tested at the manufacturing plant of another industrial collaborator Thogus Products (Avon Lake Ohio, USA). The major objective of the testing operation is to check the functional feasibility of the AM Core and compare its performance against the already existing Machined core. The injection molding machine used in this operation is ENGEL VICTORY 165. A double-cavity molding die is installed inside the injection chamber. In one of the cavities, the traditional core insert (termed as Machined Core hereafter) which was machined in MoldMAX material is fitted. MoldMAX XL alloy (from Materion Corporation) is a high strength copper alloy with good thermal conductivity. It contains no beryllium, and hardness is comparable to AISI P-20 tool steel; but the thermal conductivity is two -three times higher. They provide excellent toughness, wear resistance and surface finish. The other one was fitted with the 3D printed Maraging steel core insert (AM core). The inserts fitted on the machine is shown in Fig. 7.

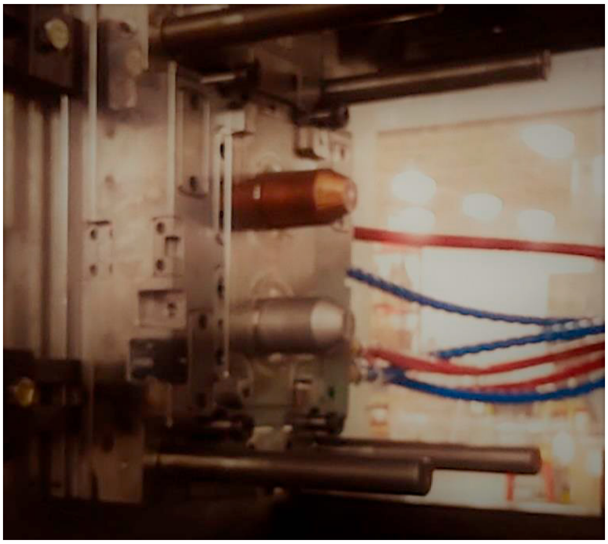

Fig. 7. Experimental setup of core inserts

The top insert of copper color in Fig. 7 is the machined core and the bottom insert of silver color is the AM core. Both the cores can be active simultaneously in production. Moreover, it is also possible to restrict production on the machined insert's cavity and keep only the AM one active; and vice versa. The injection molding machine has built in controller as well measurement and display board. It enables the determination of various in-process parameters such as cooling time, production time, pressures, clamping force etc. very easy and user friendly. In addition to that, a pressure gage, temperature gage and flow meters were also used during the experiments to take measurements relevant data. This specific injection molding tool is designed to manufacture containers utilized in automated pharmacy compounding system. The part is made of polypropylene plastic material. The final plastic product is shown in Fig. 8.

5.1. Experimental results

Two different cases are tested during the experiments. In case 1, both the cores were active and in case 2 only one single was active at a single time. Hence, for case 2, two different scenarios arose for two different inserts and they were tested separately. The measurements obtained in the experimental testing are noted down in Table 1 and Table 2.

Fig. 8. The final plastic product

Table 1. Case 1: Both cores under operation simultaneously.

Parameters measured	Unit	Machined Core	AM Core
Coolant inlet temperature	°C	21.67	20.00
Coolant outlet temperature	°C	25.00	24.44
Injection pressure	MPa	5.43	5.43
Coolant flow rate	L/min	5.678	5.30
Coolant pressure	kPa	10.34	10.34
Clamping force	MN	1.331	1.331
Total cycle time	s	32.73	32.73
Cooling time	s	18	18
Mold Temperature before operation starts			
Position 1	°C	24.44	23.89
Position 2	°C	24.50	24.28
Position 3	°C	24.50	24.33
Mold Temperature after operation ends			
Position 1	°C	24.50	25.44
Position 2	°C	25.56	32.94
Position 3	°C	25.94	39.83
Plastic Temperature before operation starts	°C	198.33	198.33
Plastic Temperature after operation ends			
Position 1	°C	24.83	27.22
Position 2	°C	25.39	29.50
Position 3	°C	34.67	38.44

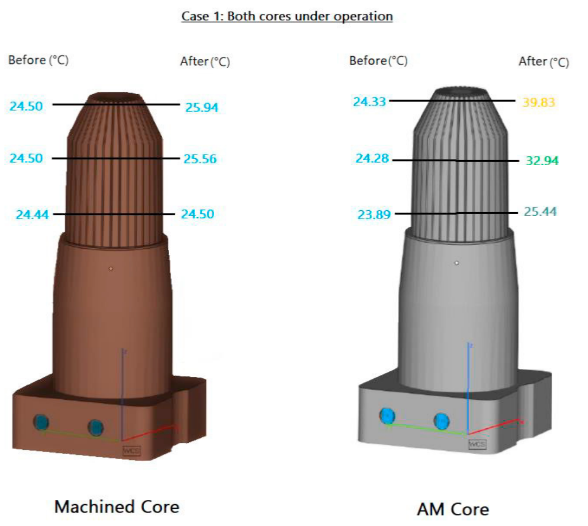

Fig. 9. Temperature on the cores in Case 1, before and after the injection molding process

Table 2. Case 2: Single core under operation at a time.

Parameters measured	Unit	Machined Core	AM Core
Coolant inlet temperature	°C	21.67	20.00
Coolant outlet temperature	°C	25.00	21.1
Injection pressure	MPa	7.23	7.14
Coolant flow rate	L/min	5.678	5.30
Coolant pressure	MPa	10.34	10.34
Clamping force	MN	1.342	1.341
Total cycle time	s	22.36	22.36
Cooling time	s	8.5	8.5
Mold Temperature before operation starts			
Position 1	°C	24.44	23.89
Position 2	°C	24.50	24.28
Position 3	°C	24.50	24.33
Mold Temperature after operation ends			
Position 1	°C	25.28	27.17
Position 2	°C	27.06	34.78
Position 3	°C	28.28	43.89
Plastic Temperature before operation starts	°C	198.33	198.33
Plastic Temperature after operation ends			
Position 1	°C	24.83	27.22
Position 2	°C	25.39	29.50
Position 3	°C	34.67	38.44

6. Results and Discussion

The major objective of the experimental tests was to determine the functional feasibility of a 3D printed core in industrial setup. Having completed a successful experimental testing, it is quite evident that the AM core is functionally capable for manufacturing relevant plastic products using injection molding operation. The coolant flowrate measures in both the cases also validate the design of the core insert. In case 1 and in case 2, the coolant flow rate in AM core is lower than in the machined core. The redesigned model enabled the water to go further inside the core, compared to the machined core, and hence this lower value of flowrate. Some other parameters such as coolant inlet temperature, plastic temperature before the operation starts, the injection pressure, the clamping force etc. are input setup parameters in the operation and have same values for both the machined core and the AM core.

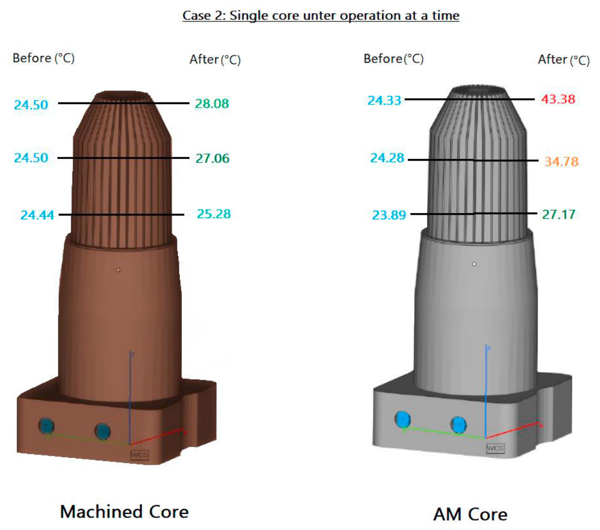

Fig. 10. Temperature on the cores in Case 2, before and after the injection molding process

In case 1, when both the cores were active, the cooling time is 18 s and the total production time is 32.73 s. The time is same for both the cores because the both of the cores are inserted in the same die. Hence the cooling performance of the cores can be analyzed using the temperature readings on the final plastic part as well as on the core insert after operation. As evident from the tables above, 3 different positions were selected on the core and the final plastic parts to assess the cooling performance. Starting from the top, position 1 is at the 1/3 of the distance lengthwise. Position 2 is 2/3 of the distance and finally position 3 is at the bottom. As the cores and the plastic part are axially symmetric, the positions provide similar temperature readings along the same distance around the periphery. The rationale of taking temperature measurements in 3 different positions is to check the uniformity of temperature distribution. From the data presented in Table 1 for Case 1, it is evident that the cooling performance of the Machined core is better than the AM core. The temperatures on the AM core and its subsequent plastic part is higher than that of the cases in Machined core. Moreover, the temperature distribution is much more uniform in machined core as well. But to really evaluate the thermal performance of the cores, it is essential to consider the thermal properties of both the materials.

The traditional machined core is made of MoldMAX material whose thermal conductivity is 70W/m-K, whereas the thermal conductivity of AM core's Maraging Steel material is only 27 W/m-K, which is around one-third of the machined core. This vast difference is thermal conductivity highly affects the performance and temperatures of the core. With this much low thermal conductivity, the temperatures in the AM core was only 5-10℃ higher than that of in the case of machined core, after the same period of time. Hence, it is evident that if both the cores were made of same material or at least with materials of similar thermal conductivity, the thermal performance of the AM core would be significantly better than the machined core. Porosity of the core is also important for its thermal performance. The 3D printed core is designed using dimensionless parameters in optimization, and the porosity of the Maraging steel traditional core is not provided by our industrial partner. Both the cores are solid models, porosity=1 is used in the design and computation.

In case 2, it is practically tested to see what the minimum possible cooling time for the AM core is to work properly and be functionally capable. With a number of trial runs, the minimum value of cooling time for the AM core was determined as 8.5 s and the subsequent production cycle time was 22.36 s. At this specific time setting, all the other readings such as coolant pressure, clamping force, temperature readings etc. were taken. Moreover, same cooling time and production cycle time value was set to check the performance of machined core in case 2, an all the temperature and pressure readings were taken thereafter. This case study was performed to see how a single core insert operates and whether it affects the operational parameters significantly. With much less cooling time than in case 1, the temperature readings in case 2 were a bit higher. Again, the performance of machined core was better than the AM core, which is actually due to the very low thermal conductivity of AM core.

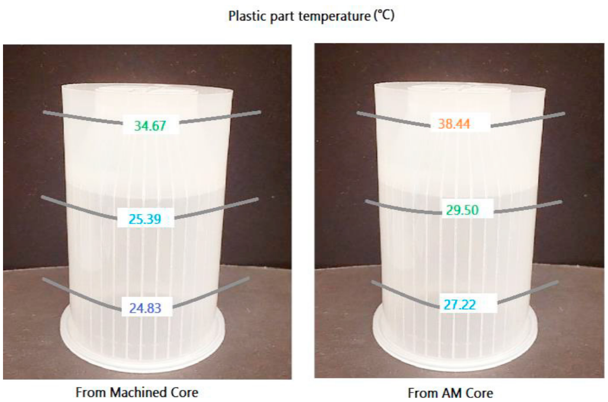

Fig. 11. Temperature on the manufactured plastic part, just after ejection

Fig. 9 and Fig. 10 shows the temperature on the cores in case 1 and 2 respectively. As mentioned in Table 1 and 2, three locations on the cores are selected to test the temperatures. The readings are taken before and after the injection molding process takes place. Before the process begins, the mold temperature is around 24 ±0.5 ℃, in all the positions, for both machined and AM core, in both cases 1 and 2. But after the injection molding process is completed and the part is produced, the temperature readings on those positions change. The core gets hotter as expected, as hot molten plastic is injected inside the mold cavity during the process. But how uniform the temperature distribution is and how close the readings are to the initial (before process) readings indicate the thermal performance and efficiency on the molds(cores) and the cooling channels. From table 1 and 2 we can get the temperature readings on position 1, 2 and 3 for both the cores in for case 1 and 2, which is also depicted in Fig. 9 and 10 for easy understanding. We can see that, the temperatures are higher in AM core in both cases, also, in position 3, the temperature is 13-14℃ higher in AM core, compared to the traditional machined core. It is also notable that there is no leakage of coolant in any of the cores. Moreover, from Fig. 11, we can also see that the plastic part which is produced from AM core exhibits higher temperature, compared to the part being produced in machined core. Though it seems that the AM core is thermally less efficient than the traditional core, it is not true. The material property needs to be considered here. As mentioned earlier, the thermal conductivity of the AM core material is about 1/3rd of the machined core. This, in fact, results in the temperature raise in the AM core. It is necessary to check the thermal efficiencies of the optimized conformal cooling channels in cores with same materials, and from the results obtained in this study, we expect to have distinctively better results for AM cores, when the thermal conductivity will be same for both the cores.

In addition to the cooling performance, dimensional accuracy and surface finish are very important for the plastic products in injection molding industry. The surface finish of the product is highly dependent on the surface finish or the mold's core and cavity. In this study, the machined had better surface finish than the AM core. The finishing of an additively manufactured core requires different stages of finishing operations to be carried out to make it production ready. It is a combination of manual and automated finishing, and is time and budget consuming. But yet, it is financially cost effective to use AM cores in long term. The 3D printed cores with optimized conformal cooling channels are supposed to provide longer service life, better cooling performance and a well-planned design and implementation process of 3D printed mold core and cavities can ensure higher business profits.

7. Recommendations

From the experimental testing, it is evident that the AM core is completely functional and effective is heat and fluid flow. The design is valid, yet to improve the thermal performance, it is crucial to use high thermal conductivity material to 3D print any such core inserts or mold tools. If any plastic injection molding industry opts to use AM molds, it is essential for them to check the thermal conductivity and other thermo-mechanical properties of the metal powder as well as the traditionally existing machined mold and thus take an informed business decision. Moreover, a 3D printed mold or core insert required several surface finishing and hybrid machining operations to be completely production ready. Hence, the designer needs to take care of the dimensional precisions while designing for additive manufacturing. With the higher rate of growth in additive manufacturing technology, it is expected that many different materials will be available in newer future to fulfill the material property requirements of industry.

8. Conclusion and Future Work

In this study, a specific thermal-fluid topology optimization method is introduced to design conformal cooling systems. The solid and fluid phase material are optimally distributed over the entire design domain. The conceptual design is converted into a three-dimensional cooling network to be implemented in redesigning an existing industrial core insert for plastic injection molding. The core is 3D printed and tested in industrial manufacturing environment and comparative performance study is completed. The results provide insight into the prospect and potential of 3D printed cores for injection molding industry. With appropriate material being used for printing, it is extremely possible to ensure faster and efficient cooling to provide business profits for the industry. The thermal property of the mold material highly influences the quality of the operation as well as the quality of the product. Materials with similar thermal properties are required to conduct a meaningful comparative analysis study. The research group is currently working on acquiring similar material machined and AM cores as well as evaluating the quality of the plastic products. It will be an actual comparative study with same geometry and same material with machined and 3D printed core. The results will be available in future publications of the research group.

Acknowledgements

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