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TURBULENCE FLOW SIMULATION OF MOLTEN METALS IN RUNNERS FOR DEFECT CONTROL IN CASTING OF A SPUR GEAR BLANK

Enesi Y. Salawu*, Oluseyi O. Ajayi, A.O Inegbenebor
Department of Mechanical Engineering, Covenant University, P.M.B 1023, Ota, Ogun State, Nigeria
*Corresponding Author

ABSTRACT

The study investigates the effects of turbulence flow of molten metal on the walls of the runner and the mould cavity during pouring via simulation approach. Effects of temperature, solidification time, shrinkage porosity, thermal modulus, hot spot formation and interfacial heat transfer coefficient were simulated under turbulent flow condition. Turbulence kinetics and flow properties which include velocity and viscosity were equally simulated. The result of temperature simulation showed an ideal variation of temperature distribution during flow and in the cavity. Molten metal at liquid state was observed to vary from 654.7-636.0 oC and became solid at 473.3-492.0 oC for a total simulation time of 169.5838 seconds. Consequently, at higher pouring temperature, diffusion of heat into the walls of the mould will occur due to the momentum of flow thereby leading to erosion of the mould content. In addition to this, velocity and viscosity of the molten metal was found to have effect on the turbulent kinetics. Thus, this simulation technique will help the foundry industry in improving the gating system design by studying the defects associated with turbulence flow and incorporating filters to remove the inclusions in the gating system

Keywords: Spur gear, Production, Failure Analysis, Turbulence

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1. INTRODUCTION

Engineering components produced using casting techniques are usually associated with high failure rate. This is can be attributed to the variations in their mechanical properties which is as a result of internal defects experienced during casting [1]. Turbulence flow of molten metals poised great effect on a runner in casting process and this include the erosion of the mould constituents such as sand, water and even the binders. Consequently, filling of the mould cavity under turbulent condition becomes a difficult task [2]. Previous study by Cui et al. [3] revealed that molten TiAl consist of physical erosion after solidification and the rate of the erosion depend on the temperature at which the liquid was poured into the mould cavity. A thermal-fluid model was developed by [4], to investigate the mass flow, momentum and energy flow of Ti–6Al–4V ingot cast neglecting turbulence. Although the model was able to predict the thermal flow pressure fields at steady state conditions. Study has showed [5] that turbulence kinetics is crucial to the quality of solidification and this is evidenced by the heat transfer and latent heat evolved during solidification. Thus, turbulence kinetics is critical to the accurate prediction of casting quality when simulating [6]. According to [7], improper control of turbulence and heat transfer of molten metals would result into surface erosion and entrapment of slag particles which subsequently lead to poor quality in castings. Based on this, Khan et al. [8], developed a multiphase flow model to reduce the effect of turbulence of molten metal during pouring process using different Tundish system. The computational fluid dynamic model was validated via simulation and the result showed that dam and weir reduced the effect of turbulence during pouring. In a similar vein, Jafar-Salehi et al. [9] carried out the effect of fluid flow and heat transfer on molten metal solidification using a numerical simulation approach. The result showed that thermodiffusion affected the mass transfer rate which have a considerable impact on turbulence kinetics of the fluid flow. Furthermore, metals at liquid state exhibit some level of complexity such as pressure change during flow thereby causing variations like expansion and contraction of runner's geometry and eventual erosion of the walls [10,11]. Moreso, turbulence flow is noted with high momentum and this is critical in the filling process of the mould especially when complex parts are to be produced. Over reliance on experimental knowledge becomes a problem [12]. Obviously, the turbulence kinetics of molten metals has both microstructural and tribological effects on the filling process [13]. According to Kermanpur et al. [14], shrinkage in the casting of automotive brake pad was inevitable using experimental approach, however from simulation of the same process, decrease in temperature of the molten metal will significantly reduce shrinkage problems. Thus, experimental and simulation of filling processes of mould cavity contribute greatly to the final shape of the product [15,16]. For instance, the stress developed by spur gears in most machines are usually attributed to internal flaws in the manufacturing process especially when casting method is used. This will result to increased downtime, material wastage and low product quality [17,18,19]. In this study, a general purpose simulation software called PROCAST was used to simulate the thermal properties of the flow of molten metals during spur gear blank casting. Based on the integrated Finite Element method, it can predict internal distortions and stresses and can address more casting problems such as solidification time, turbulence kinetics and time to solidus. The simulation result was used to investigate the thermal behaviour of the molten metal in the runner.

2. PROBLEM DEFINITION

Molten metals are usually associated with unsteady turbulent flow especially at high pouring temperature. This problem usually causes casting defects which includes to mention a few hot spots and shrinkage porosity. Hot spots referred to the regions of thermal isolation which cool last to form cavities in the final product. Turbulence and intense density of molten metals lead to oxide formation and mould erosion and eventual formation of porosity in the final casting. A typical example of effect of turbulence is illustrated in figure1.

Figure 1 Shrinkage and porosity [20]

The analysis of failed track shoes revealed the presence of shrinkage and porosity during solidification of molten metal. Thus it becomes imperative to understand the processes of filling via simulation approach before casting the parts.

3. METHODOLOGY

cylindrical gear blank and gating system was modelled in Solidworks 2018 version. This was imported into PROCAST 2017 to simulate the various thermal properties of the molten metal. This includes temperature, fraction solid, solidification time, time to solidus, shrinkage porosity chvorinov's thermal modulus presence of hot spots and interfacial heat transfer coefficient. Moreso, certain fluid properties of the molten metal were simulated which includes fluid velocity magnitude and directions, pressure, turbulent energy, turbulent dissipation, turbulent viscosity, filling time, air entrapment flow length and oxide formation. Figure 2 presents the Solidworks model of the gear blank and the gating system.

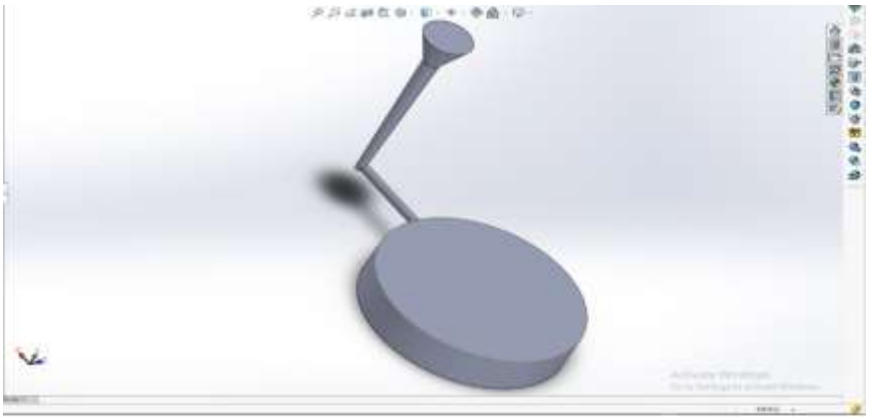

Figure 2 Gear blank and Gating System Design

4. RESULTS AND DISCUSSION

4.1. MEASURE OF TEMPERATURE DURING POURING

Figure 3 presents the simulation result of temperature variation in molten metal during pouring. The molten metal temperature at liquid state was seen to vary from 654.7-636.0 ^{o}C and became solid at 473.3-492.0 ^{o}C for a total simulation time of 169.5838 seconds.

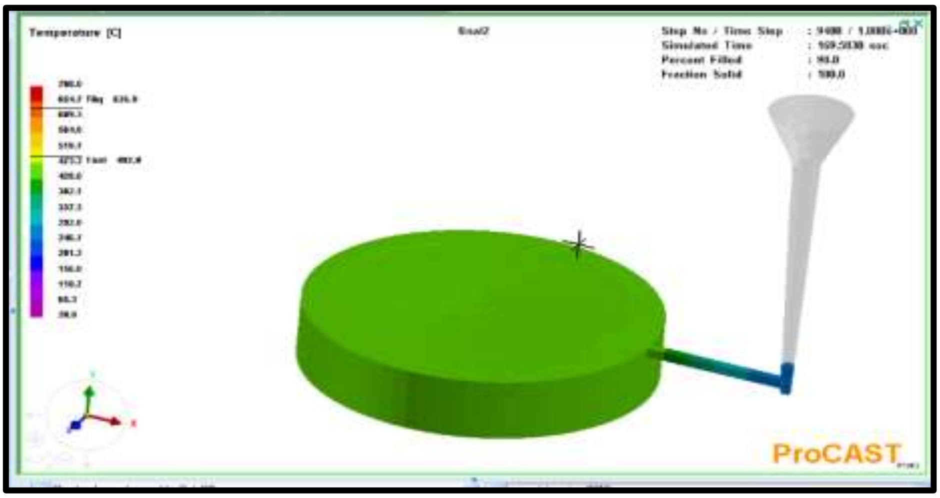

Figure 3 Temperature variation of molten metal during pouring

Pouring molten metal at high temperature leads to distortion along the walls of the runner or cavity and reduction in the volume filled because molten metal diffuse heat more than momentum and erosion of the mould content due to turbulent.

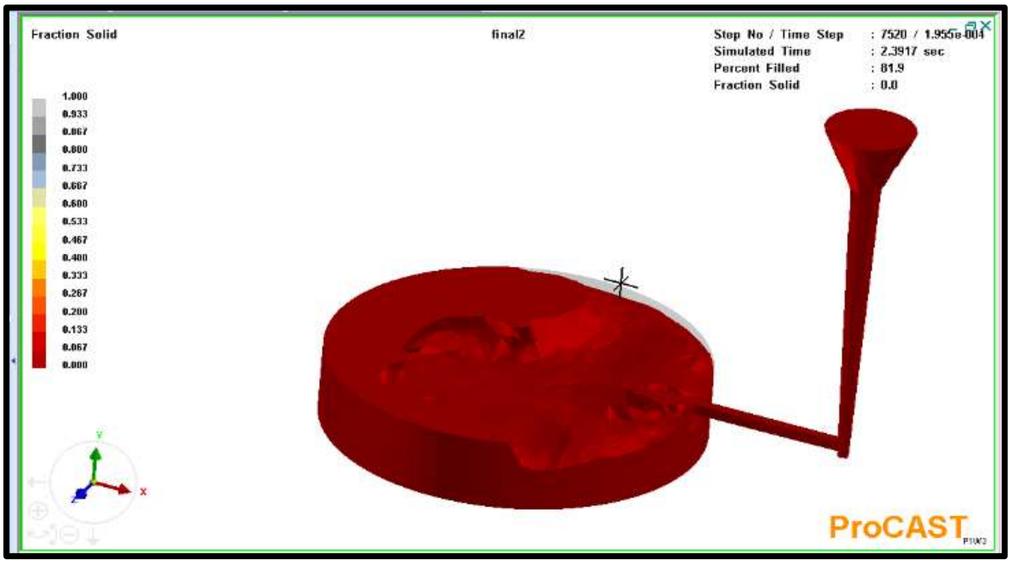

Figure 4a Variation in fraction of solid

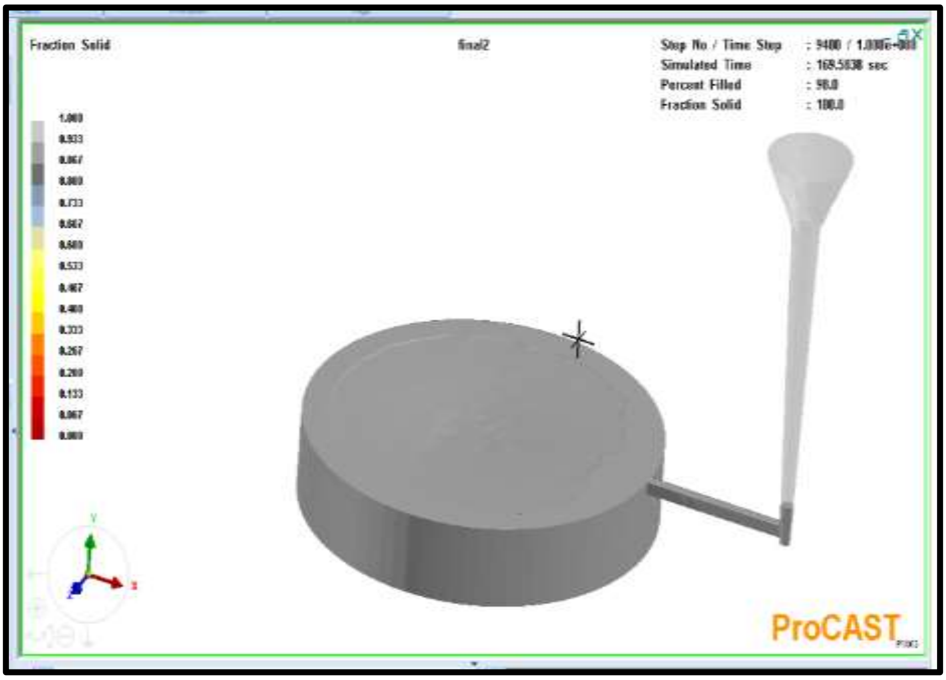

Figure 4b Variation in fraction of solid

4.2. Fraction Solid formation profile

Figures 4a and 4b showed the variation in the formation of fraction solid during molten metal flow. Point 0 indicates no fraction of solid was formed during pouring. As pouring continued with time, different level of fraction of solid were formed and total solidification of the molten metal was completed. It can be observed from figure 4a that with percentage filling of about 81.9, no fraction solid was observed. But 100% fraction solid was achieved with 98% volume filled in figure 4b. Though, this can be attributed to the time factor.

4.3. Variation of Solidification Time

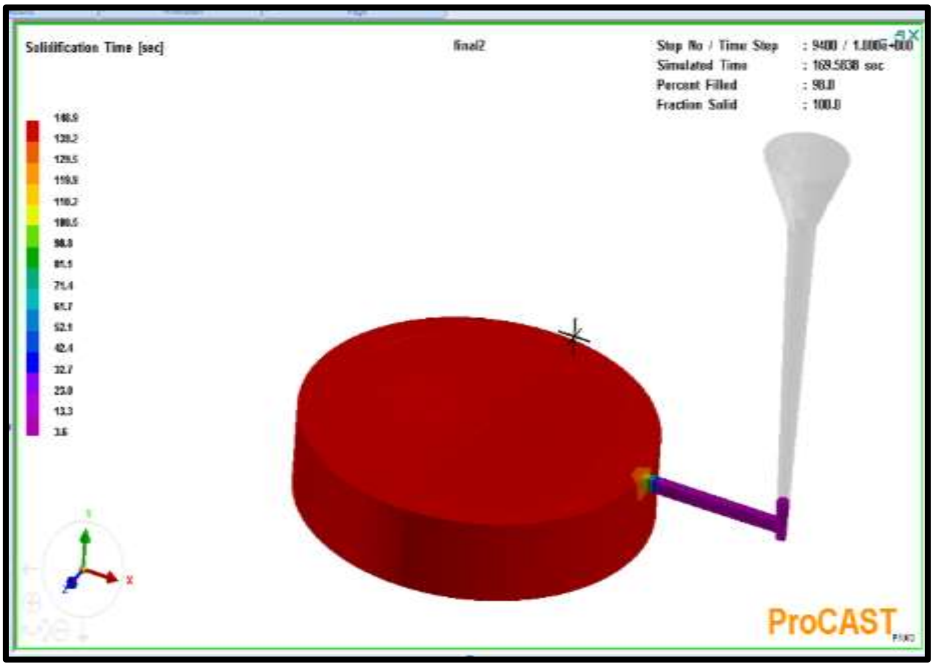

Figure 5a Solidification Time

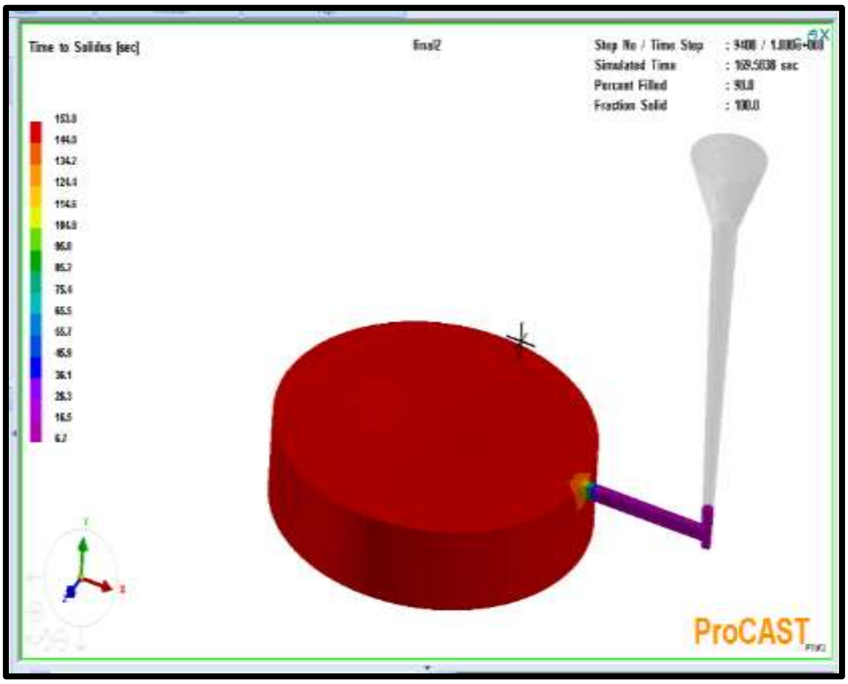

Figure 5b Time to Solidus

Figures5a and 5b revealed the variation in the solidification time and time to solidus. From figure 5a, it could be observed that the solidification time took about 148.9seconds while from figure5b, it took the molten metal a total of 153.8seconds to become completely solidified. The longer the solidification time, the more the level of porosity in the casting, especially in aluminium alloy casting.

4.4. Effect of Shrinkage porosity and Chvorinov's Thermal modulus

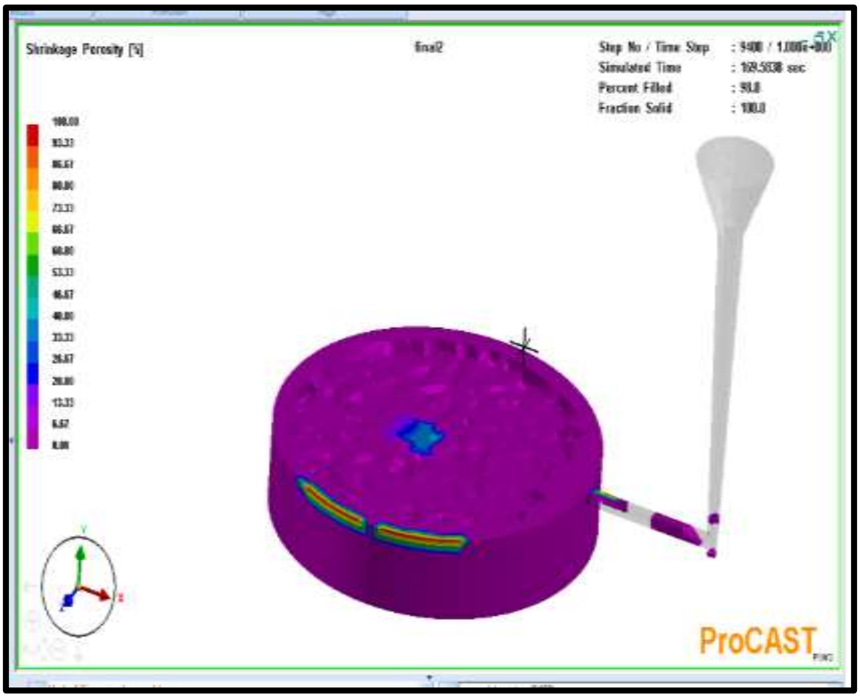

Figure 6 Effect of Shrinkage Porosity

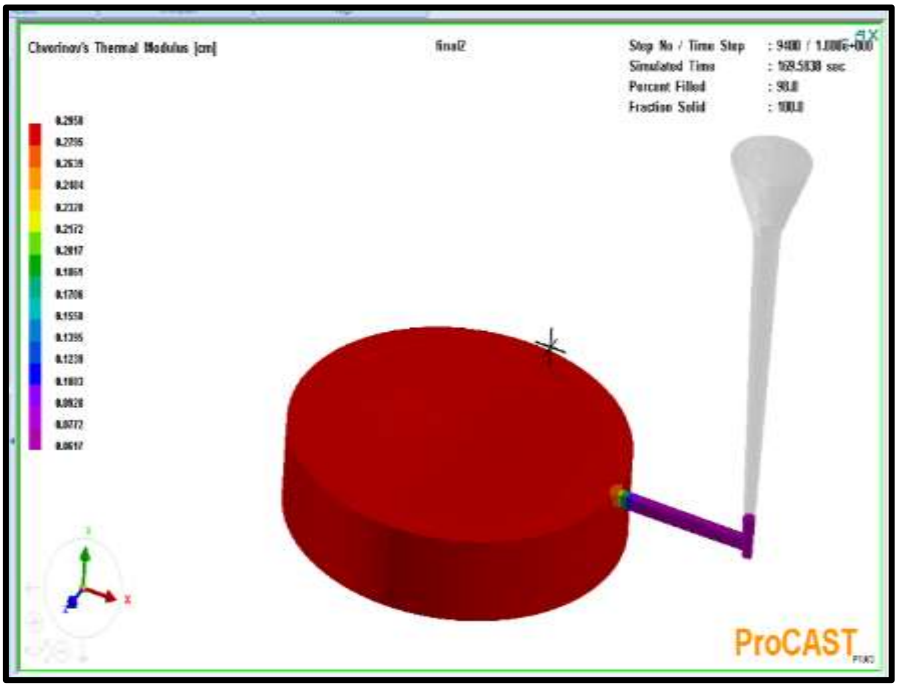

Figure 7 Chvorinov’s Thermal modulus

Moreso, figure 6 presents the result of variations in the shrinkage porosity along the runner and mould cavity in a turbulent flow condition. It can be observed that shrinkage occurred both in the runner and the mould cavity. However, the size of the shrinkage porosity and location determines its influence on the quality of casting. If it is bigger and located at the edge of thick sections, then it will ultimately distort or weakens the casting. Also figure 7 showed the Chvorinov’s thermal modulus result which is the equivalent modulus during the period of casting and was evaluated from the solidification time using the Chvorinov’s rule. From the result and based on this rule, it can be depicted that casting with small volume and increased surface area cools more rapidly compared with casting with small surface area and probably large volume. This implies that the time taken for the molten metal to solidify is a function of the section modulus.

4.5. Hot spot formation and Interfacial heat transfer coefficient

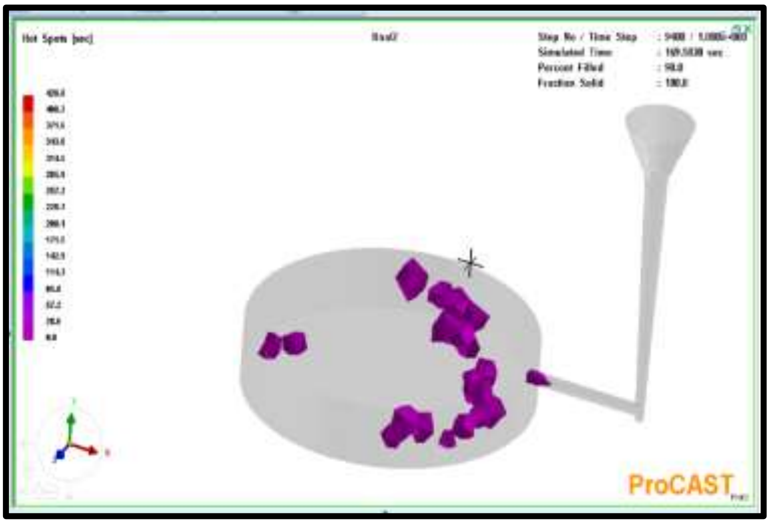

Figure 8 Hot spot formation

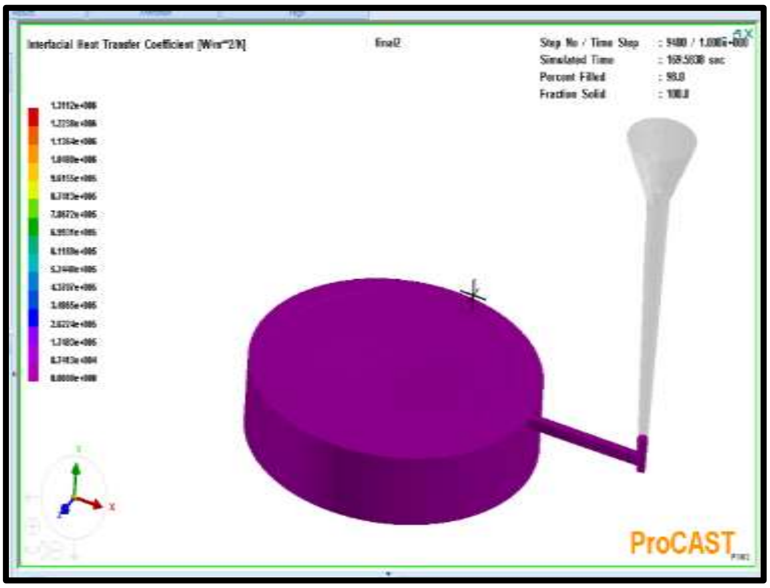

Figure 9 Interfacial heat transfer coefficient

Figure 8 revealed different hot spots formed in the mould and the runner. Turbulence flow resulted to formations of regions which are thermally isolated and eventually cools last and form cavities in the casting. This isolated molten metal is sometimes formed in the solidified casting and the shrinkage effect would be observed at the top of the hot spot as seen from figure 8. Also, figure 9 is a result of variation in the interfacial heat transfer coefficient under turbulent flow conditions. This is vital in predicting a reliable casting process that can reveal the formation of hot spot and residual stress [20]. However, the linear variation in the heat transfer coefficient as compared to the variation in temperature of casting can be associated with the formation of air gap between the mould surface and the casting. Thus, the heat distribution profile has helped in accurate simulation and prediction of the solidification process during casting.

4.6. Analysis of molten metal velocity and magnitude

Figure 10-13 presents the result of velocity variation under turbulent flow condition. We can assume that the fluctuation in turbulent flow are the same in all direction, hence the turbulent flow velocity variation can be treated as isotropic. Thus, figure 11-13 showed that frequency in velocity variation is a function of the height of the sprue. Increase in sprue height will result to reduction in turbulence velocity and less defect. Fluctuation in velocity magnitude and direction at the runner due to turbulent flow will result to shrinkage porosity both at the runner and in the mould.

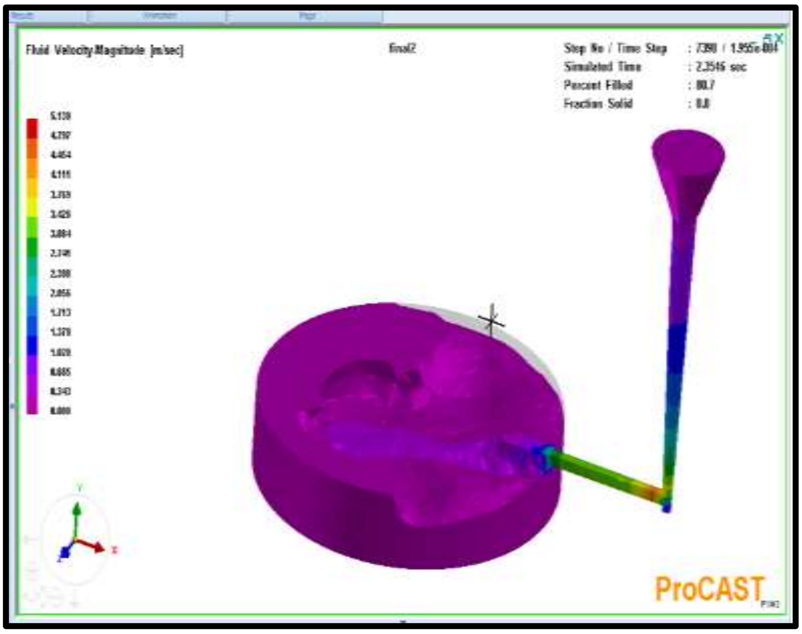

Figure 10 Fluid velocity magnitude

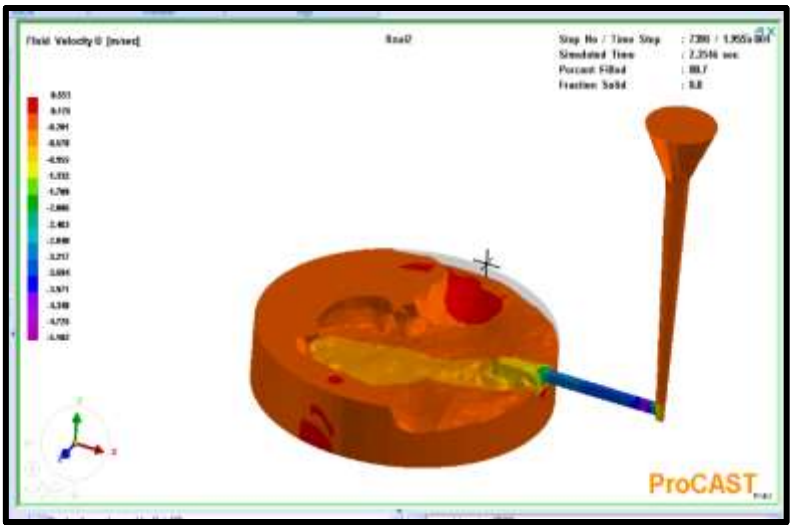

Figure 11 Fluid velocity in U-direction

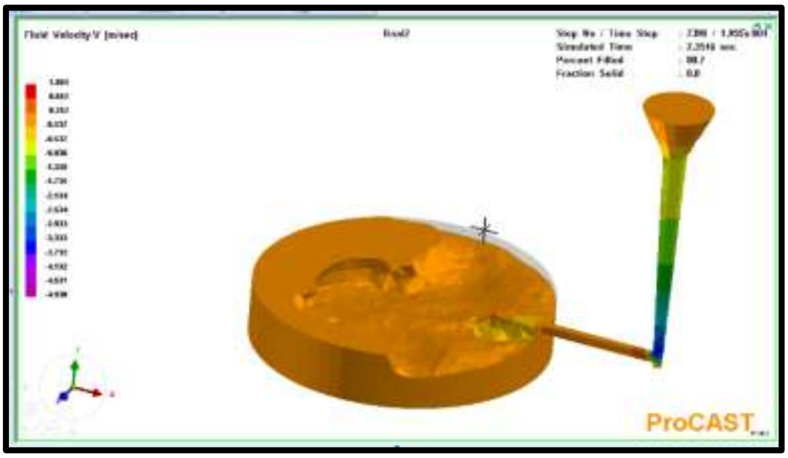

Figure 12 Fluid velocity in V-direction

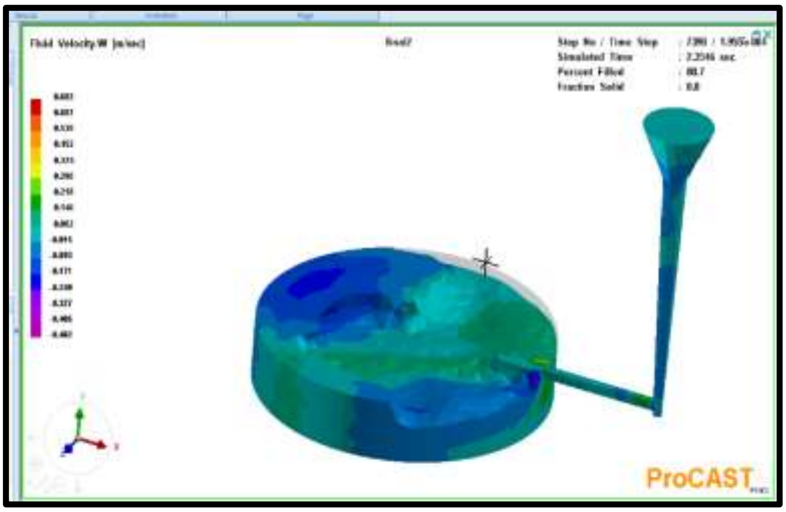

Figure 13 Fluid velocity in W-direction

4.7. Turbulence Analysis

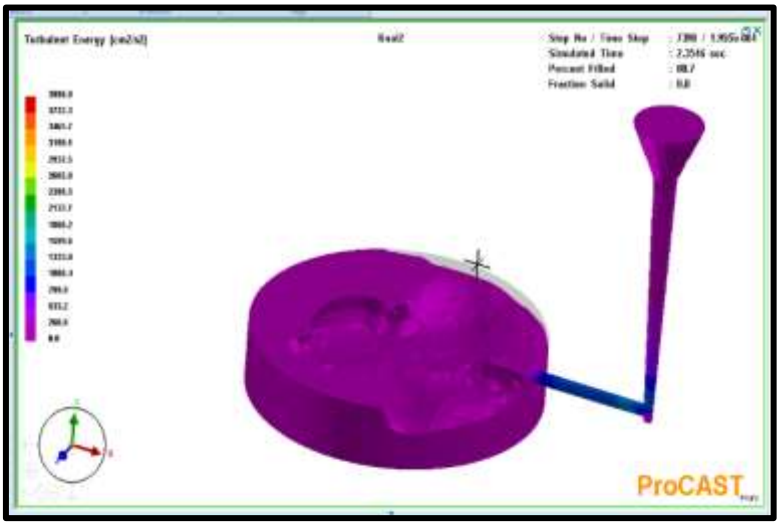

Figure 14 Turbulent Energy

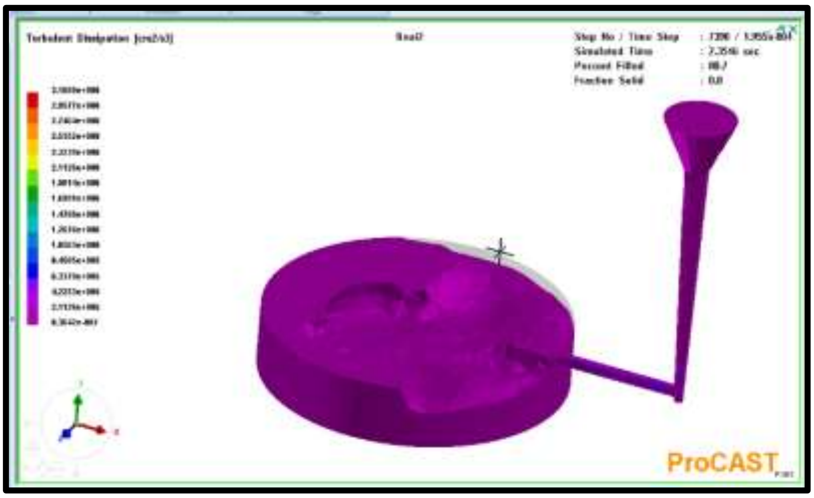

Figure 15 Turbulent Dissipation

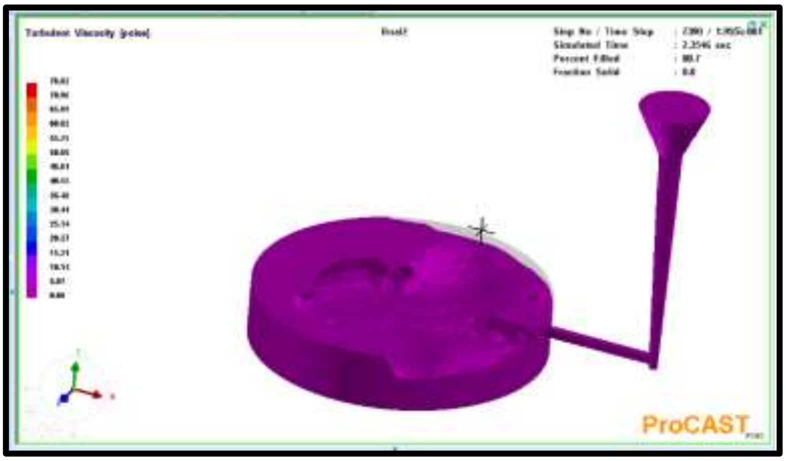

Figure 16 Turbulent Viscosity

Figure 14-16 presents the kinetic energy fluctuation and turbulence viscosity of the molten metal due to the swirling motion of the fluid through the runner. The results showed the momentum increase throughout the runner to the mould due to fluctuations in turbulent velocity. In turbulent flow, we expect that the velocity of the fluid should be higher and this is a function of the viscosity which implies that lower viscosity increases the liquid velocity and high turbulence energy dissipation. At higher temperature increase in turbulence is noticed and this is detrimental to the mould content.

5. CONCLUSION

Pouring and solidification of molten metal in the mould is a critical design step in casting process. This is because the liquid behaviour as it solidifies and cools determine the quality of the cast. Based on this, this study critically examined the thermal behaviour of molten metal with emphasis on the turbulence kinetics via simulation approach. The thermal properties which include temperature, thermal modulus, shrinkage porosity, hot spot formation, interfacial heat transfer were simulated. More so, several factors that influence flow were equally considered which include; velocity, viscosity and the various turbulence motion were simulated. The result showed an increased turbulence was achieved due to increase in velocity and also very obvious at increased temperature. Thus pouring of liquid metal at higher temperature erodes the wall of the runner and reduce the volume of the liquid metal due to higher momentum and heat diffused by the molten metal. The study has revealed the various defects associated with turbulence flow especially when the thermal effects of the molten is considered. The approach will be useful to the foundry industries by incorporating filters to separate dirt and inclusions in the gating system design so as to have smooth and minimum turbulence.

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