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Research Article

Numerical and Experimental Study on the Impact of Insulation in Centrifugal Casting

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ABSTRACT

There is significant increase in use of metals across various engineering, household and industrial applications along with continuous evolving process of manufacturing to produce precise shape and finish of components. Previous studies have mainly focused on mould pre heating to manage thermal gradients while the present work examines an alternate approach by the use of thermal insulation to reduce the heat loss during casting. Transient thermal investigation of the centrifugal casting mold was done in this work. In order to assess the heat transmission properties for both insulated and non-insulated mold surfaces and comprehend how different solidification rates affect the end quality of castings produced, ANSYS simulation software was utilized for analysis. Different insulation conditions were tested mechanically, and scanning electron microscopy (SEM) was used to look into microstructural differences. According to the findings, applying mold insulation along with preheating and rotating at an optimal speed improved heat retention and decreased heat loss by 27%. This results in better solidification, fewer casting flaws, and higher-quality cast products, accompanied by a 12.67% decrease in the outer mold surface temperature.

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INTRODUCTION

With ongoing developments in the extraction of raw materials and their conversion into completed products for engineering purposes, materials have been used for centuries. For forming metals into intricate shapes, one of the most ancient and popular production processes is still in use today. Typically, the procedure is melting raw materials, putting them into a mold of the appropriate size and shape, and then letting them harden into the desired shape. When traditional gravity casting is compared with centrifugal casting, the efficiency of centrifugal casting has become more significant in producing cylindrical components, since the cast is produced by the centrifugal forces developed during the rotation of the mould with less defects. Its inherent dynamic operation characterized by rapid phase transitions, high temperature gradients, and complex solidification behaviour. These kind of factors often lead to casting defects such as porosity, inclusions or non-uniform grain structures, which can influence the end application

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performance of the product. The grain structures formed during solidification is especially crucial as it directly affects the strength and durability of the component. For both metallic and non-metallic materials, such as glass and concrete, centrifugal casting is widely employed because it provides better control over crystal development and solidification, improving the quality and dependability of the casting.

It is very much important to understand the process, metal flow behaviour and influence of process parameters in production of casts with good quality. Though there are several studies addressing various aspects of cylindrical casting, a significant scope still exists to optimize and refine the process for better overall performance. All of which are closely linked to casting process parameters [1,2]. Researchers have investigated various parameters to study their effects on microstructure and interfacial bonding in bimetal castings. Some of the key process parameters include mould's rotational speed [3-5], the preheating temperature [6], the temperature of the first solidified layer [7], melt pouring rate [8], temperature of superheat of the melt, and the rate of cooling of the mould during casting.

A critical aspect in the production of castings through centrifugal casting lies in understanding the heat dissipation within the rotating mould, since the manner in which molten metals lose heat during this process profoundly influences their solidification rates [9,10], subsequently impacting the final properties of the castings. Thus, the present study focuses on performing numerical heat transfer analysis of the mould. By exploring the rate of heat transfer and controlling its mechanisms with and without insulation of rotating mould, we can explore the process well so as to optimize the casting process to achieve superior quality and performance of the resulting metal components.

In addition to heat transfer mechanisms, the study also goes through the evaluation of mechanical properties of the cast specimens. Various parameters such as mould length, the use of thermal insulation are examined in order to understand how they affect the final quality of the castings produced. Along with this, Scanning Electron Microscopy (SEM) is used to analyze the surface finish and microstructure and structural characteristics. The approach of combining all these not only improves our understanding of the casting process but also offers a comprehensive evaluation of casting quality developing the way for advancements in engineering applications that demand strong and reliable materials.

MATERIAL AND METHODS

ANSYS Simulation

The fluidity of the melt has a very vital part in the production of high quality, defect free castings [11], since it determines how effectively the molten metal can fill the mould cavity before solidification begins [12]. Adequate fluidity ensures smooth flow of the molten metal throughout the surfaces of the mould, reducing the defects such as porosity, cold shuts, and incomplete filling. However, maintaining sufficient fluidity is often challenging due to the rapid heat transfer that occurs from the molten metal to its surroundings due to high temperature differences, which

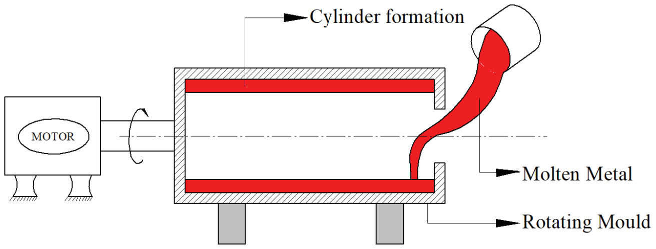

Figure 1. Schematic diagram of principle of Horizontal centrifugal casting process.

Table 1. Material Properties of Mould & Insulating layer

Particulars	Mould	Insulating Layer
Material	Mild steel	Asbestos
Thermal conductivity (W/ mK)	55	0.08
Specific Heat (J/kgK)	500	810
Thickness (mm)	10	25
Heat Transfer Coefficient (W/m^{2}K)	111.08	111.08
Coefficient of thermal expansion (/^{0}C)	10.8 to 12.5 x 10^{-6}	5 x 10^{-6}

can lead to premature solidification [13]. In order to overcome this issue, one of the widely used approach is reducing the temperature difference by preheating the mould [1,6,7] before the molten metal, which delays the solidification, due to retaining of heat in molten metal for a longer duration than usual and hence flow of the melt will be better. As a result, the metal flows more uniformly, improving the mould filling and improving the overall casts quality.

In this study, an additional strategy along with mould pre heating has been explored by incorporating an insulation layer around the rotating mould. This strategy is designed to further minimize the loss of heat from mould's inner surface to the surrounding air, effectively slowing down the rate of heat transfer, and hence there is more time for the molten metal to flow smoothly promoting better filling and improved casting quality. The rationale behind this modification is that by insulating the mould, the heat loss to the external environment is minimized, and the melt has additional time to settle and solidify into the required shape.

The below Figure 2 (a) to Figure 2 (h) shows the results of simulation for a mould of length 45mm, with and without insulation.

The insulation layer serves as a barrier [14], slowing down the cooling rate and enabling more controlled solidification, which is mainly useful when involved with high-viscosity [11] or high-melting-point metals that require extended fluidity [15].

To investigate the effects of this insulation on the fluidity and cooling behavior of the molten metal, transient heat transfer analysis was conducted with ANSYS v19.1 workbench software. There were two different mould dimensions considered with/without insulation for the simulation. The rate of heat transfers between the melt,

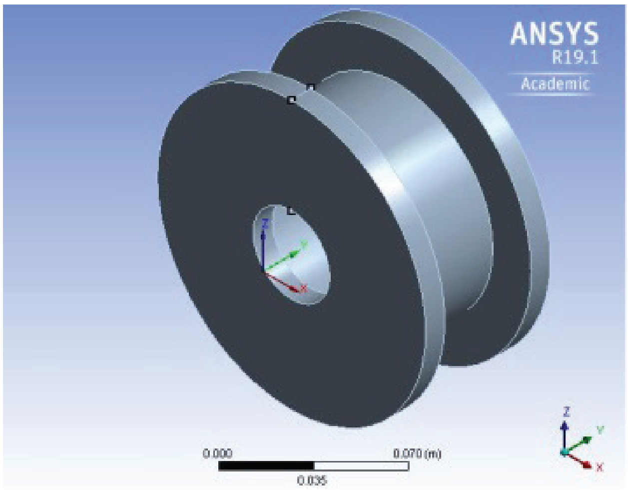

Figure 2. (a) CAD model of Mould without insulation.

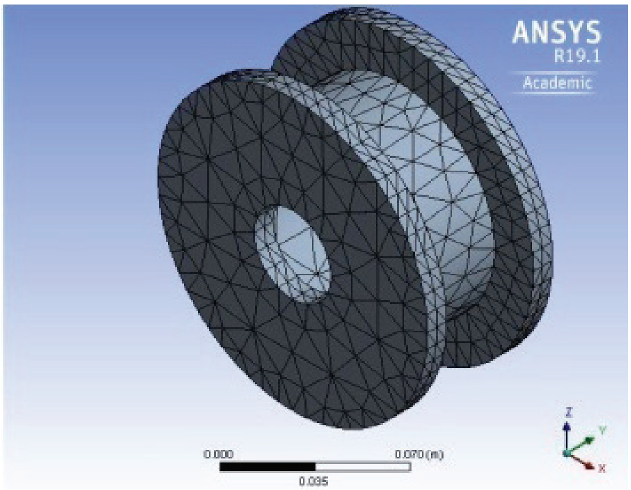

Figure 2. (b) FE Model of Mould without insulation.

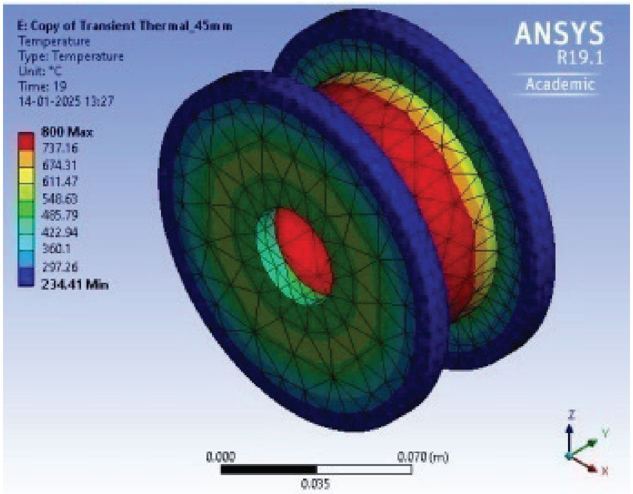

Figure 2. (c) Temperature of Mould without insulation.

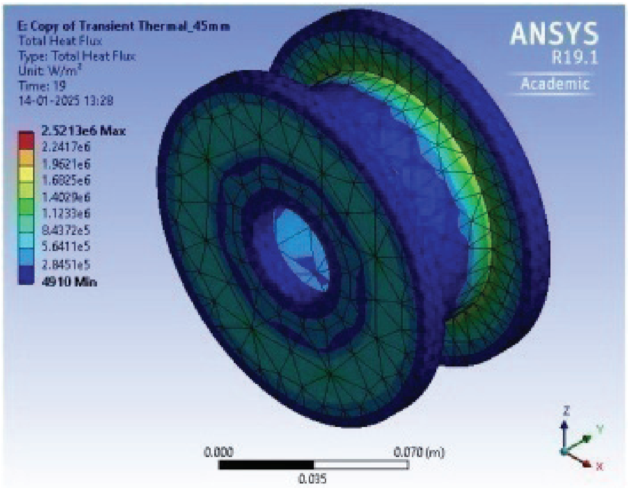

Figure 2. (d) Heat Flux in Mould without insulation.

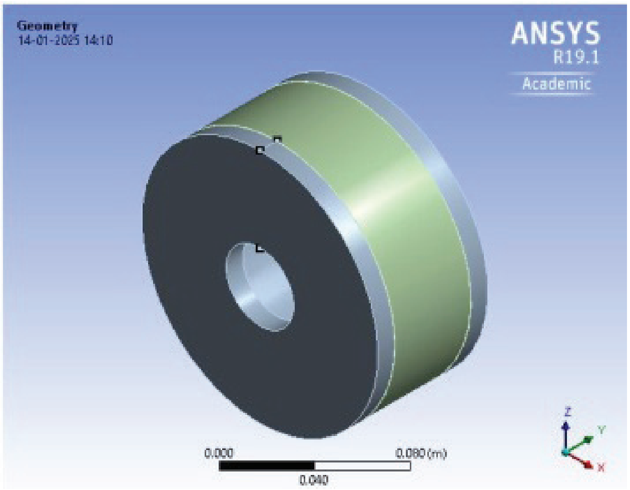

Figure 2. (e) CAD model of Mould without insulation imported into ANSYS.

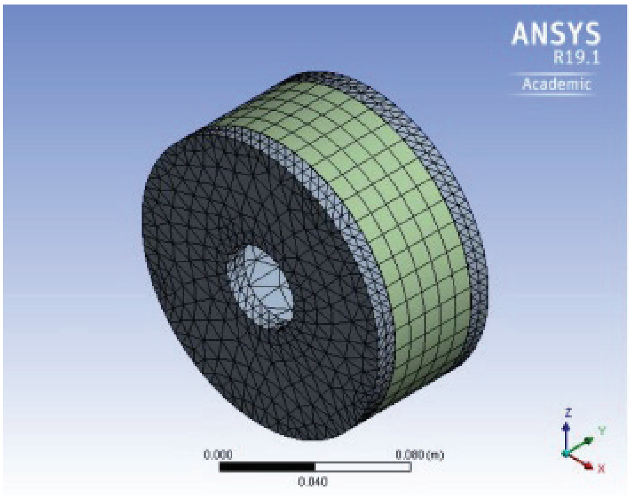

Figure 2. (f) FE Model of Mould without insulation in ANSYS.

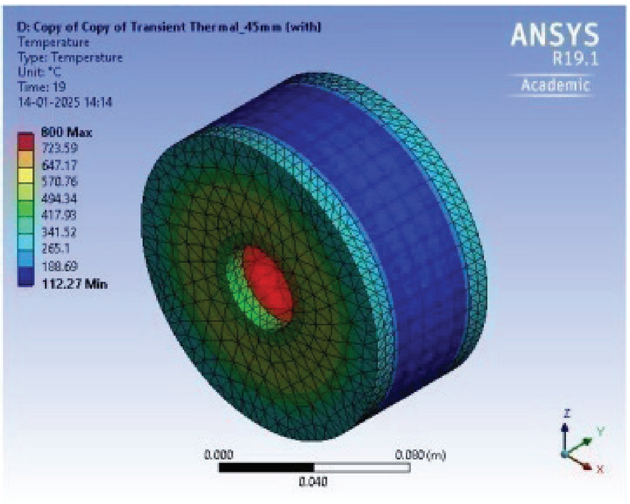

Figure 2. (g) Temperature of Mould with insulation.

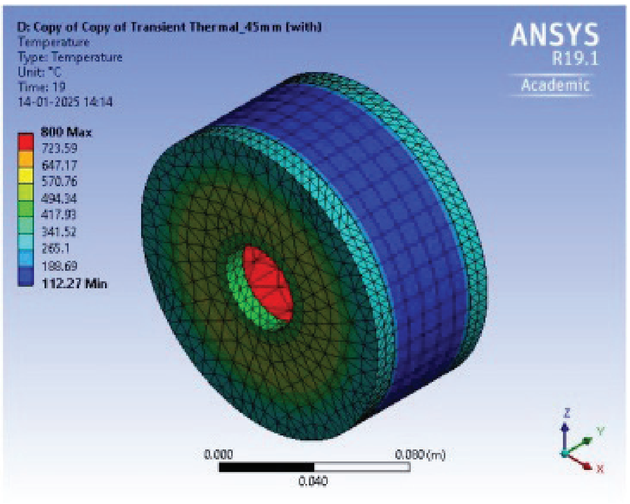

Figure 2. (h) Heat Flux in Mould with insulation.

mould and surroundings were analyzed with particular focus on the temperature distribution [16] and the cooling rates over time. The properties of the mould material and molten metal as shown in the Table 1 above were the inputs the simulation model.

Theoretical Comparison

The results from simulation were validated along with the theoretical calculations to validate the analytical and theoretical results of transient thermal behaviour of the rotating mould. The theoretical validation carried out using MATLAB, a largely used tool known for its numerical and analytical capabilities. Heat transfer equations were employed in MATLAB, along with material properties, geometry, and boundary conditions that was used in simulation. This method enabled to get accurate estimation of heat flux and temperature distribution, which was validated with ANSYS results. The main inputs included thermal conductivity, density, specific heat capacity and mould dimensions along with thickness of insulation. Boundary conditions used were constant inner surface temperature and surrounding convective heat transfer coefficient. The heat transfer equations were solved using finite difference method.

Governing equation

The two cases of the mould with and without insulation of the rotating mould are presented in the Figure 3 (a) and Figure 3 (b). The transient heat transfer for a cylindrical body is given by;

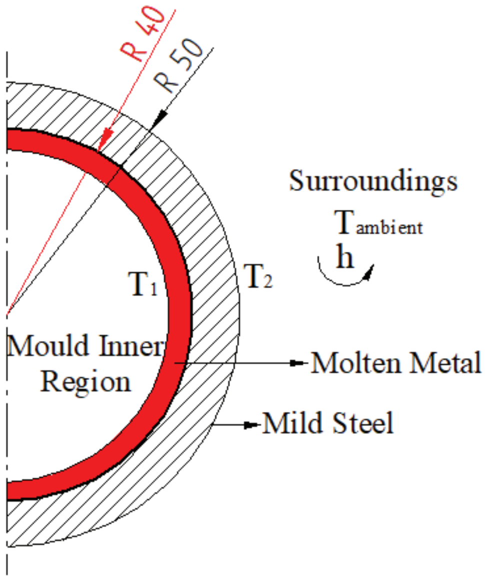

Figure 3 (a) Mould Without insulation.

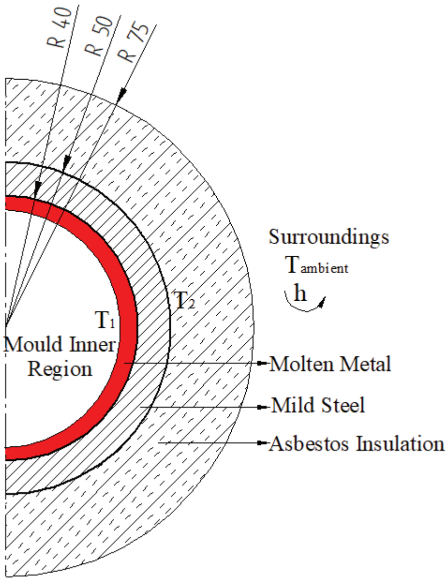

Figure 3 (b) Mould With insulation.

$$\frac{\partial T}{\partial t} = \frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \tag{1}$$

Where, temperature is represented as T in °C, time t in s, radius r of cylinder, thermal diffusivity α in m^2/s. The initial temperature is set to $T_{ambient} = 30°C$ and boundary conditions like $T(r, 0) = T_{ambient} = 30°C$, inner surface at $r = r_i$, $T(r_i, t) = 800°C$ and at outer surface $r = r_0$, heat loss due to convection; $-k\left(\frac{\partial T}{\partial r}\right)_{r=r_0} = h(T(r_0, t) - T_{ambient})$ are applied during time step. Heat flux at the outer surface is calculated as $q_{outer} = -k\left(\frac{\partial T}{\partial r}\right)_{r=r_0}$, while the average outer surface temperature is calculated using $T_{avg.outer} = T(r_0, t)$.

The above case is for transient thermal analysis of the mould without insulation. If the insulation layer needs to be considered then the heat conduction now spans into two regions as follows;

Region 1: Mild Steel ($r_{inner} \leq r \leq r_{cylinder}$)

$$\frac{\partial T_1}{\partial t} = \frac{\propto_1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right) \tag{2}$$

Region 2: Asbestos ($r_{cylinder} \leq r \leq r_{outer}$)

$$\frac{\partial T_2}{\partial t} = \frac{\propto_2}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right) \tag{3}$$

Where, $\propto_1$ and $\propto_2$ are the thermal diffusivity of mild steel and asbestos respectively. T_1 temperature of the mould at the inner surface and is considered as same as the molten aluminum temperature assuming that there is negligible heat loss from the melt poured from furnace. T_2 is the temperature at outer surface of the mould in both with and without insulation cases. In first case for mould without insulation the thermal conductivity k in boundary condition equation is considered as $k_{mildsteel}$ and for second case where the mould is insulated the value of thermal conductivity k in above boundary condition equation is considered as $k_{asbestos}$. The heat transfer coefficient is considered as h in both the cases. The heat transfer from the mould outer surface to surrounding is considered as forced convection since the mould in rotating at 1000 rpm the air particles around the mould will be in motion.

Finding value of heat transfer coefficient

In this present study, the system functions under dynamic conditions because of the mould's high rotational speed. This makes it challenging to accurately determine the heat transfer coefficient (h), a key factor that strongly affect the overall thermal behaviour [17]. Under these conditions, the heat transfer is primarily dominated by forced convection which results from continuous relative motion between rotating mould surface and the surrounding air.

Factors Influencing the Heat Transfer Coefficient (h);

1. Mould Geometry & Dimensions
2. Material Properties
3. Insulation Considerations
4. Rotational Speed and Turbulence Effects
5. Ambient and Surface Temperature Conditions

We know that outer radius of the mould (r_{outer}) = 0.05m, Rotational Speed (N) = 1000 rpm, then Angular Velocity $(\omega) = \frac{2\pi N}{60}$. Therefore the outer Surface Velocity (v) can be found as $\omega * r_{outer}$.

Now noting down the Air properties at the film temperature $(T_f) = \frac{T_{outer} + T_\infty}{2}$ and finding the Reynold's no (Re) using the formula $\frac{v\, D_{outer}}{\nu}$. We have for forced convection around a cylinder, the empirical correlations for R_e in the range of 40,000 – 400,000, we have; $Nu = C.\ Re^m.\ Pr^{0.333}$, where C = 0.0266 and m = 0.805.

Now using $\mathrm{Nu} = \frac{h\,D_{outer}}{k}$
we can find the value of h using
$h = \frac{Nu*k}{D_{outer}}$.

Though practically there exist dynamic conditions, forced heat transfer coefficient could be considered because of mould rotation as mentioned above. Finite difference method (FDM) is used for discretizing the heat equation in radial direction and time and the results from solving the above partial differential equation are obtained from MATLAB.

Experimentation

With wide variety of process parameters already studied in precious researches, the presence of insulation on to the mould which is rotating is done in this present study. The experimental set up consisted of a Horizontal centrifugal casting machine, which is capable of rotating upto 2000 rpm. To compare the type of casts produced with the parameter of insulating the thickness, Aluminum metal was chosen, due to its abundance availability and one of the easy to cast metals. The properties of Aluminum metal are as shown in Table 2 below.

Table 2. Material Properties of Aluminum

Particulars	Value
Density (kg/m^3)	2,660
Thermal Conductivity (W/mK)	237
Specific Heat (J/kgK)	900
Elastic Modulus (MPa)	70,300
Melting Point (^{0}C)	660
Poisons ratio	0.3

Production of Casts

The Aluminum was melted in and electric furnace with a super heat temperature of 150°C so as to melt the metals for casting. Hence the molten metal temperature is considered as 800°C at the inner surface of the mould in case of simulation and MATLAB.

The mould with constant rotational speed of 1000 rpm was considered in order to understand the type of casts we obtain with and without insulating the mould. The superheated molten aluminum at 800°C is taken from the furnace and poured into the rotating mould. The heat losses from the melt from furnace to centrifugal casting machine are ignored in this study. Also the rotation of the mould at high speeds to produce the cast is a dynamic condition which will lead to consideration of forced convection between the surrounding and outer surface of the rotating mould, leading the greater heat transfer coefficient values. This dynamic condition is also not considered in the study; instead it is assumed that the mould is in static condition in case of ANSYS simulation as well as MATLAB calculations.

Figure 4 (a) and Figure4 (b) shows the two cylinders casted from horizontal centrifugal casting machine with and without insulation respectively. In both cases, the mould was rotated at 1000 rpm while molten pure aluminum metal at 800°C was poured into the rotating mould. The mould was not pre heated while it was at ambient temperature before pouring the molten metal. It can be observed from Figure 5 (a) that the inner surface finish of the finished cast is rough when compared to the one in Figure 5 (b) This is because of the smooth flow of melt

Figure 4. (a) Mould without Insulation.

Figure 4. (b) Mould with Asbestos Insulation.

Figure 5. (a) Cast cylinder without Insulation.

Figure 5. (b) Cast cylinder with Asbestos Insulation.

inside the rotating mould [12], since an added insulation with asbestos around the rotating mould reduces the heat loss as discussed in previous chapters, and allows fractionally more time for solidification.

SEM Analysis

The SEM images presented in Figure 6 (a), Figure 6(b), Figure 7 (a) and Figure 7 (b) illustrate the microstructure of aluminum castings produced by centrifugal cas.ting at identical rotational speeds, both with and without mould insulation. The images presented aforesaid were captured along the circular direction of the inner surface of the castings. From literatures it can be noticed that mould rotational speed significantly influences microstructure formation, when the speed of rotation of mould is increased which directly affects the rate of solidification of the melt. When the melt is poured into the rotating mould, the centrifugal force drives the molten metal outward, which leads to rapid conduction of heat through the ould and already solidified layers (if any) resulting in faster cooling rates.

By adding the layer of insulation around the mould, the heat loss is reduced, allowing more time for the molten metal to flow over the inner surface of the mould with uniform solidification [11]. Microstructures produced show rougher grain finished as shown in Figure 6 (without insulation) while finer grains can be seen due to smoother flow of molten metal as shown in Figure 7 (with insulation). It is evident that both rotation speed and insulation has an impact on the grain formation. Quick cooling rates without insulation leads to coarser grains whereas slower more controlled cooling with the help of insulation leads to finer grains comparatively due to more gradual solidification.

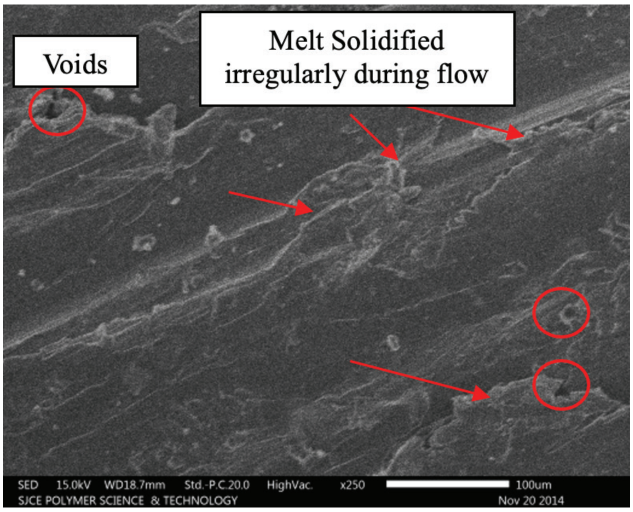

Figure 6. (b) SEM image-2 of Al cast without insulation.

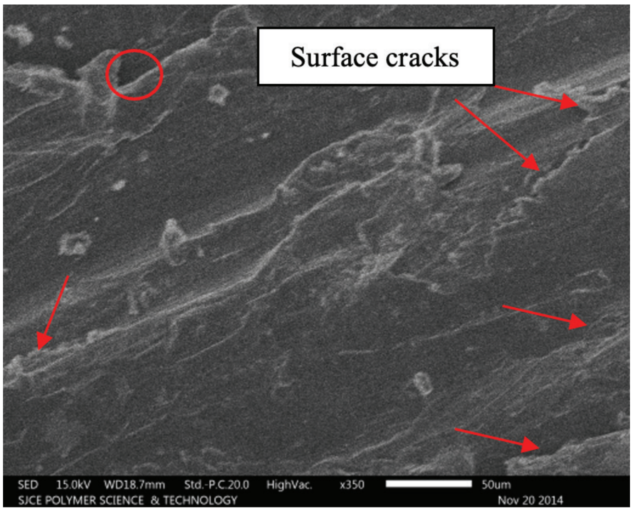

Figure 6. (a) SEM image-1 of Al cast without insulation.

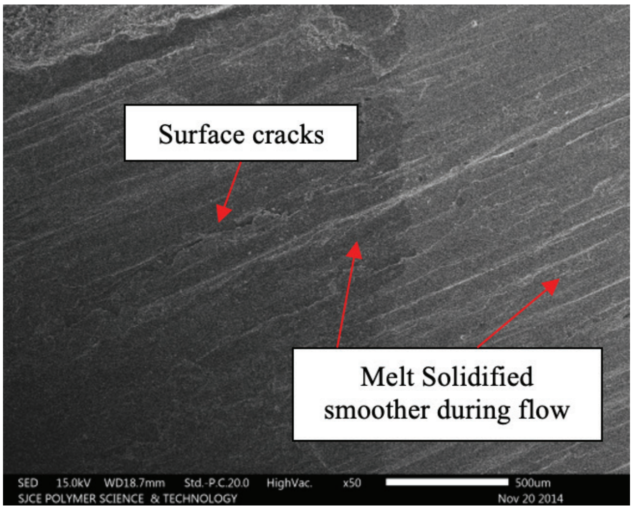

Figure 7. (a) SEM image-1 of Al cast with insulation.

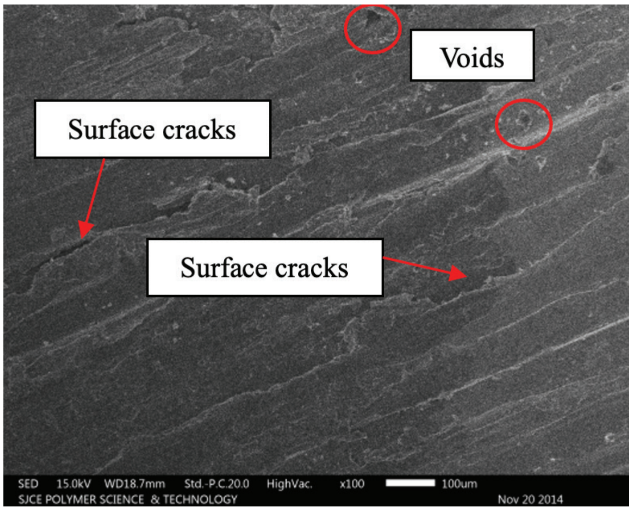

Figure 7. (b) SEM image-2 of Al cast with insulation.

RESULTS AND DISCUSSION

The mould in the centrifugal casing machine was first analyzed in ANSYS workbench software, for studying the rate of heat transfer behaviour. The simulation was done for two cases which are (i) with and (ii) without insulation for two different mould lengths of 70 mm and 45 mm. The results obtained from ANSYS simulation were compared with that obtained from MATLAB where the governing partial differential equation of the heat transfer was solved using finite difference method to compare the results from ANSYS. The results of both are presented in Table 3 below;

Figures 8 (a) and 8 (b) illustrate that the simulated and theoretical results for heat flux, both with and without insulation, show strong agreement. Similarly, Figures 9 (a) and 9 (b) compare the theoretical and simulated results for the average temperature distribution at the outer surface of the mould under insulated and non-insulated conditions, also demonstrating excellent correlation.

The results obtained from MATLAB programming as well as ANSYS simulation shows considerable similarity there by validating that the results are accurate.

The Figure 10 (a) shows the comparison of results of average heat flux over the mould for with insulation and without insulation. As depicted in the above Figure 10 (a), it can be observed that the insulation of the mould plays a significant role in reduction in heat loss which substantially allows more heat to stay inside the mould as we can see in the average temperature distribution is reduced at the outer surface of the mould as shown in Figure 10 (a).

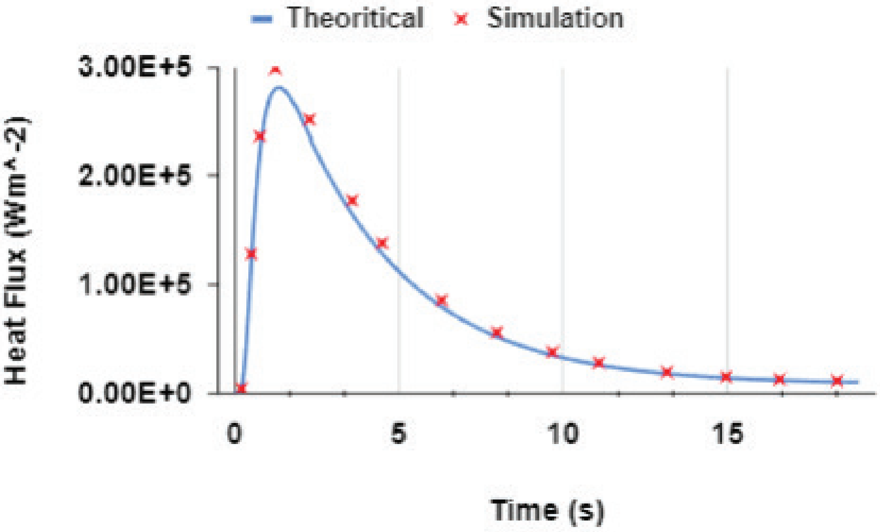

Figure 8. (a) Comparison of Theoretical and Simulation Heat Flux without Insulation.

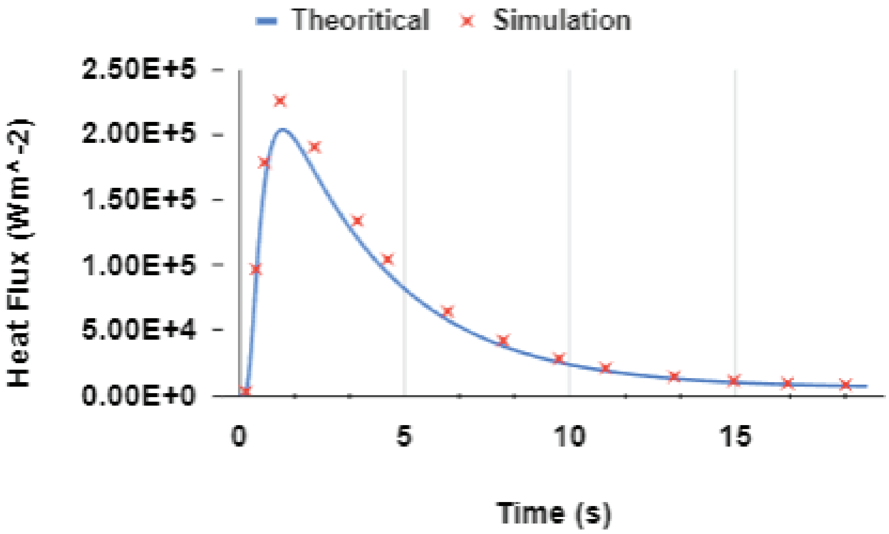

Figure 8. (b) Comparison of Theoretical and Simulation Heat Flux with Insulation.

Table 3. Results from ANSYS and MATLAB

Parameter	Insulation	MATLAB	ANSYS
Max Heat Flux (x 10^5 W/m^2)	With	2.265	2.039
	Without	2.997	2.809
Average Temperature at outer surface of mould at 19s (^{0}C)	With	689.27	668.59
	Without	792.26	765.58

Figure 10 (a) presents a comparison of heat flux results obtained from ANSYS Workbench simulations and MATLAB computations. For the insulated mould, the simulation predicts a peak heat flux of 2.039×10^5 W/m^2, while for without insulation of mould, it is 2.809×10^5 W/m^2. The MATLAB results exhibit good correlation, with error margins of 11% and 6.69%, respectively.

Figure 10 (b) presents the average temperature distribution at mould's outer surface. It can be observed from the above results that, average maximum temperature at

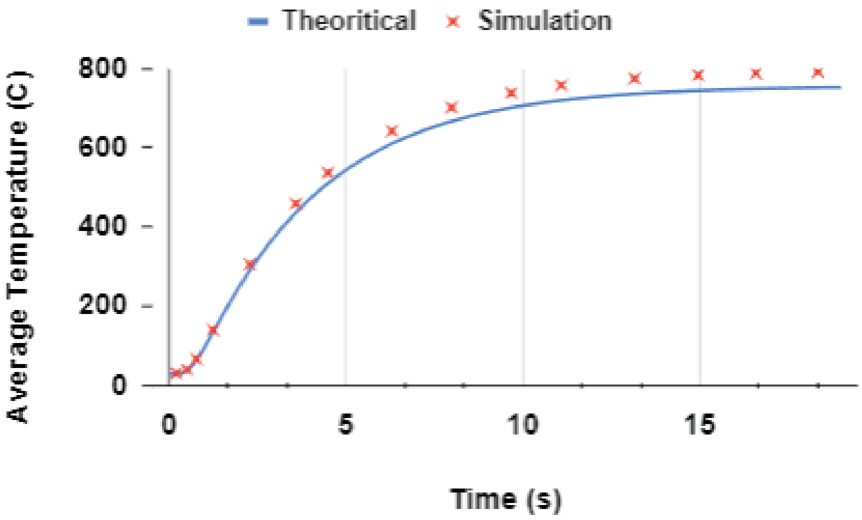

Figure 9. (a) Comparison of Theoretical and Simulation Average Outer Surface of Mould Temperature without Insulation.

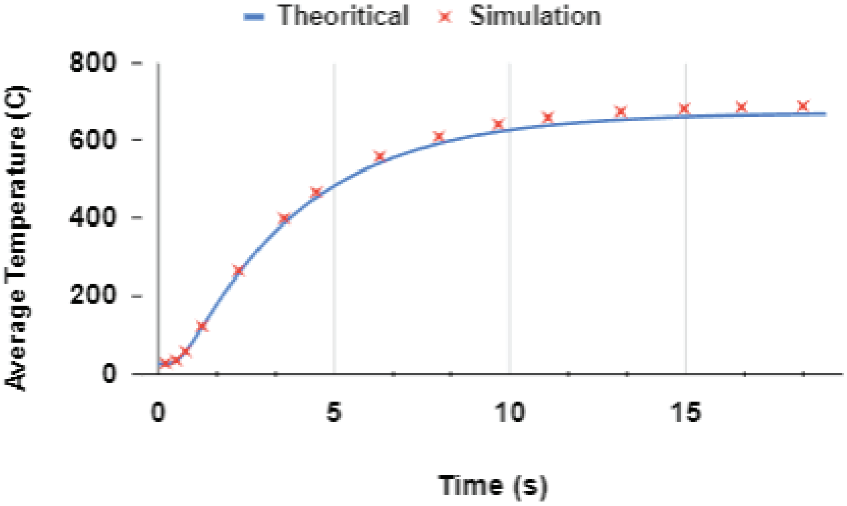

Figure 9. (b) Comparison of Theoretical and Simulation Average Outer Surface of Mould Temperature with Insulation.

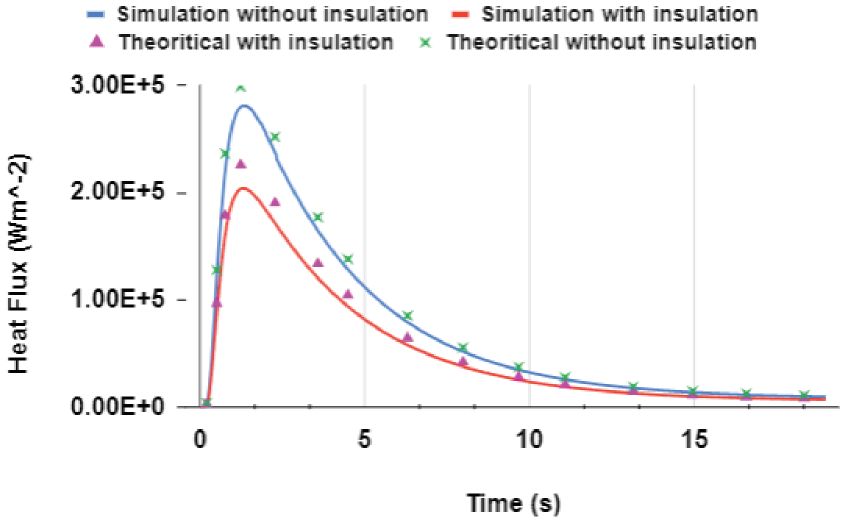

Figure 10. (a) Comparison of Average Heat flux of the Mould with and without Insulation.

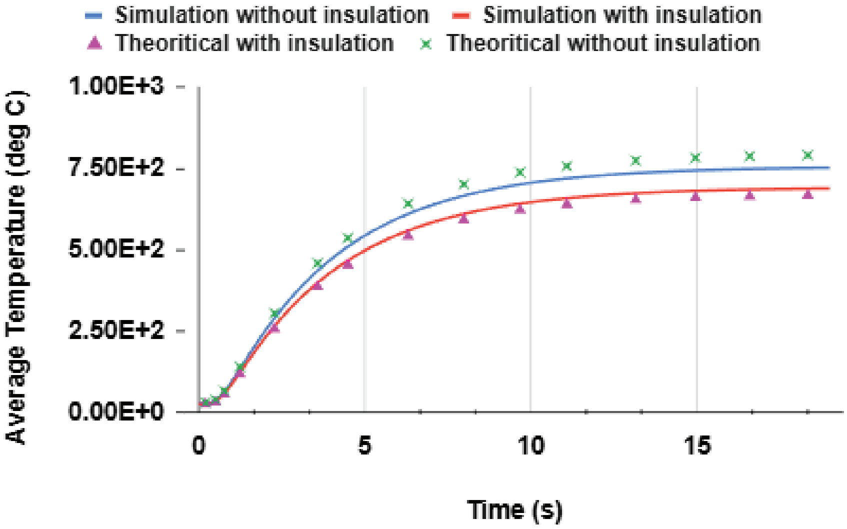

Figure 10. (b) Comparison of Average Temperature of the Mould outer surface with and without Insulation.

the outer surface reached 668.59°C for mould with insulation and 765.59°C for mould without insulation. The theoretical calculations are in good agreement with simulation results, with a few deviation of 3.09% and 3.49% respectively.

The presence of additional heat inside the mould aids the solidification rate, by increasing the time for the molten metal to solidify [14]. This reduction in solidification rate allows the molten metal to flow better [11] inside the mould as it rotates at certain speeds, hence better grain structure can be obtained comparatively which can be witnessed in the sample specimens fabricated with horizontal centrifugal casting machine with a rotational speed of 1000 rpm and without preheating the mould as shown in Figure 5 (a) and Figure 5 (b).

CONCLUSION

In this present study the effectiveness of adding an insulation layer around the rotating mould in order to improve the quality of casts produced from centrifugal casting machine and also obtain defect free castings are demonstrated The combination of transient thermal analysis using ANSYS software and theroritical validation using MATLAB and experimental observations, the study shows that the mould insulation substantially reduces the heat loss and provides lesser temperature gradients during the casting process. The key findings of the present study are shown below;

- Heat Loss reduction by 27.41% due to thermal insulation, enhancing the thermal efficiency.
- Average outer surface temperature of the mould was decreased nu 12.67% with insulation reducing the thermal gradients.
- Presence of insulation, reduced heat loss and smoother flow of molten metal leading to more uniform solidification minimizing the defects.
- The overall quality of the castings are improved with better surface finish without post processing of casts, with fewer defects.
- The results obtained from ANSYS simulation and MATLAB calculations are in good agreement.
- Finer and better microstructure grains observed in casts produced with insulated mould.

In comparison to process parameters studied in previous literatures such as rotational speed of mould and preheating, addition of insulated layer is proved to be a highly effective method for improving the cast quality with minimum defects. Future work can be focused on optimizing the insulation materials, thickness and extending the analysis to 3D thermal fluid simulations for better understanding of solidification process. Advance microstructural analysis and real time thermal monitoring can also be considered to enhance the quality of casting process.

NOMENCLATURE

$T_{ambient}$	Surrounding Temperature (°C)
$T_{average\ outer}$	Average Temperature at outer surface of the mould (°C)
T_f	Film Temperature (°C)
r_i	Inner radius of the rotating mould (m)
r_0	Outer radius of the rotating mould (m)
k	Thermal Conductivity (W/mK)
$k_{mildsteel}$	Thermal Conductivity of mild steel(W/mK)
$k_{asbestos}$	Thermal Conductivity of asbestos (W/mK)
h	Heat Transfer Coefficient (W/m^{2}K)
t	Time (s)
v	Kinematic Viscosity (m^2/s)
q_{outer}	Average Heat flux at outer surface of the mould (W/m^2)
ω	Angular Velocity (rad/s)
N	Speed of rotation of mould (rpm)
v	Outer Surface Velocity (m/s)
Re	Reynold's no
Nu	Nusselt no
Pr	Prandtl no
SEM	Scanning Electron Microscope
CAD	Computer Aided Drafting
FE	Finite Element
FEM	Finite Element Method
FDM	Finite Difference Method

AUTHORSHIP CONTRIBUTIONS

R Allwin Yesuvadian: Conceptualization, Methods, Experimentaiton, Writing – Original Draft and Editing of Manuscript. K S Keerthiprasad: Supervision, Validation and Review.

DATA AVAILABILITY STATEMENT

The authors attest that the information in the article supports the study's conclusions. Upon reasonable request, the corresponding author will provide the raw data supporting the study's findings.

CONFLICT OF INTEREST

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