Article

Investigation of the significance of numerical and physical parameters on a plane wall heat transfer

Dedhy Prihtiantoro [1*]

[1] Department of Manufacturing Engineering Technology, Akademi Inovasi Indonesia, Salatiga 50721, Central Java, Indonesia
* Corresponding: dedhyprihtiantoro@inovasi.ac.id

ARTICLE INFO

Submitted 15 Jun 2024
Revised 28 Jun 2024
Accepted 30 Jun 2024
Published 31 Jul 2024

Abstract.
Heat transfer is a process that underlines many engineering applications. A part's temperature distribution and heat flux as an effect of heat load can be analyzed for technical and economic justification. Computation has been easier with computational software based on numerical methods. The numerical method is about approximation; therefore, validation is necessary to verify the accuracy. A comparison of numerical and analytical methods on a plane wall thermal analysis had confirmed that the result from ANSYS fluent satisfies the computation. The results were strengthened by the negligible error when comparing the analytical and numerical methods. An extended study was performed to investigate the significance of numerical and physical parameters on the result further. The numerical parameter does not seem to have a significant effect, yet the physical parameters do. The study can be employed to predict the generated heat flux from various parameters under predefined operating conditions.

Keywords: heat transfer; numerical methods; analytical validation

INTRODUCTION

The Second Law of Thermodynamics entails that heat will spontaneously flow from a hotter body to a colder one, and heat will not naturally shift from a colder to a hotter body without having external energy. Therefore, a heat transfer will occur where a temperature difference exists in a static substance. One heat transfer mechanism is conduction, i.e., heat is transported in a medium due to temperature differences. The medium where heat is transmitted should be able to transfer heat, known as thermal conductivity [1]. This is a transport property, which indicates the energy transfer rate by the conduction process. In addition, whenever a temperature gradient exists in a material, a heat flux throughout the material will be generated. Heat flux is the rate of heat transfer per unit area.

Temperature distribution and heat flux generated due to temperature difference on a part can be examined and therefore the behavior of the part under certain circumstances can be recognized. This understanding is essential to drive material selection that compromises technical and economic considerations.

The advancement of computational fluid dynamic (*CFD*) software has been making the life of engineers easier when conducting engineering analysis. Most engineering cases can be modeled and analyzed. However, since most *CFD* software methods are only approximated by finite elements, finite volume, finite difference, or else, validation with experimental and analytical methods is still necessary. Therefore, a simple and fundamental case is preferred in this study to investigate the accuracy of the numerical method of ANSYS Fluent in performing thermal analysis.

LITERATURE REVIEW

One-dimensional Steady-state Conduction

A temperature disparity must exist for heat transfer to occur. Heat transfer may occur through a solid material, known as conduction. For conduction to happen, a material should have thermal conductivity, i.e., the ability of a material to conduct heat. One-dimensional means that only one coordinate is necessary to explain the spatial variation of the dependent variables. Therefore, in a one-dimensional system, temperature gradients follow a single coordinate direction, and heat transfer occurs solely in that route [2]. Steady-state thermal conduction is a condition where heat transfer occurs at constant heat flux with temperature distribution independent of time [3].

The simplicity of one-dimensional steady-state models has been a satisfying approximation of numerous engineering cases. A plane wall is commonly used to begin one-dimensional steady-state thermal analysis. In the plane wall, the temperature is a function of x and heat is transferred only in this direction. Figure 1 describes a plane wall to represent a furnace wall, where the inner surface is exposed to a temperature T_1. A conduction heat transfer occurs from the hotter inner wall throughout the thickness of the wall to the outer surface wall at T_2. Temperature distribution along the wall and the heat flux generated due to temperature difference can be analytically and numerically solved.

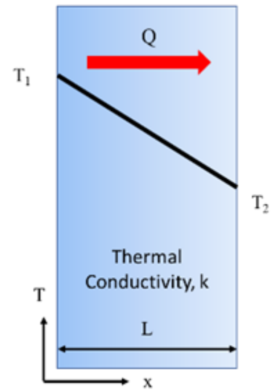


Figure 1. Plane wall

Governing Equations

The temperature at the point of interest x for steady-state conditions adhere to the following equation [2]:

$$T_{(x)}=(T_{(2)}-T_{(1)})\frac{x}{L}+T_{(1)} \quad (1)$$

In a one-dimensional, steady-state conduction plane wall without heat generation and constant thermal conductivity, the temperature varies linearly with x.

The conduction heat rate (Q) follows Fourier's law, where k is thermal conductivity and A is the cross-sectional area [2]:

$$Q_{(x)}=-kA\frac{dT}{dx} \quad (2)$$

Heat flux ($\dot{q}$) is the conduction rate per cross-sectional area; hence the heat flux is [2]:

$$\dot{q}_{(x)}=\frac{Q_{(x)}}{A}=-k\frac{dT}{dx} \quad (3)$$

$$\dot{q}_{(x)}=\frac{k}{L}(T_{(1)}-T_{(2)}) \quad (4)$$

Numerical Method

The finite Element Method is one of the numerical methods used to approach complex engineering problems related to structural analysis, fluid flow, heat transfer, and many others. This method is demonstrated to be able to solve complex engineering problems. The basic concept is dividing a domain into numerous sub-domains called finite elements, and then reuniting the sub-domain to obtain the solution. The approximation in finite elements can be refined if more accurate solutions are expected. Consequently, the solution generated from finite element analysis should compromise uncertainties that impact the accuracy of its results [4].

The procedure of conducting finite element analysis with ANSYS [5] has been modified to reflect the steps conducted in this study, which started with (1) constructing the part in a solid modeler. If the part had to be divided into numbers of tiny elements, they should be assembled at some stage. Once the part is established, the next step is to (2) select the element type. Selecting element type based on the shape of the part is a preference. (3) Meshing the part with adequate mesh properties requires prudent consideration. The capability of a computer to execute the computation might be limited to certain iterations before the memory gives up. When performing the analysis, there should be some engineering judgments, for instance, considering a fine mesh quality at the region where heat flux is concentrated and medium/coarse mesh at the area where lower loads are anticipated. ANSYS offers an automatic meshing method, as shown in figure 2 (a), which is usually simple and fast compared to tetrahedron (figure 2b) because the number of nodes and elements increase in magnitude at the same element size. (4) The material is then selected and assigned to the body of the part. The material properties might be adjusted to reflect the actual case. (5) The boundary and operating conditions are then applied to the model. Finally, (6) the computation is run to solve the equation. (7) The result can be viewed immediately, provided there is no error with the model.

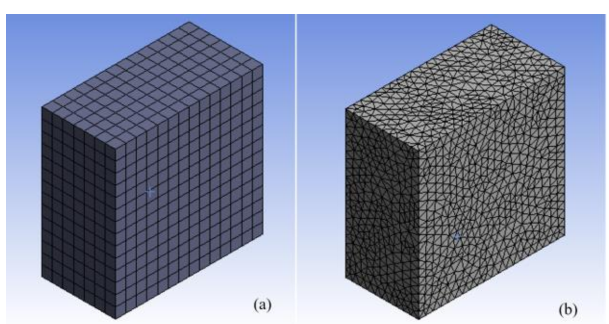


Figure 2. Meshing Configuration (a) Hexahedral; (b) Tetrahedron

METHODOLOGY

The thermal analysis study on the plane wall will be conducted as shown in Figure 3. It started by modelling the physical shape and then continued discretization by selecting elements and meshing method. The material was then assigned to the body for the properties can be incorporated in the computation accordingly. Once the boundary conditions are established, the solution can be run. If the error is acceptable, the study can be further extended. Otherwise, the element and meshing might need to be refined to satisfy the approximation.

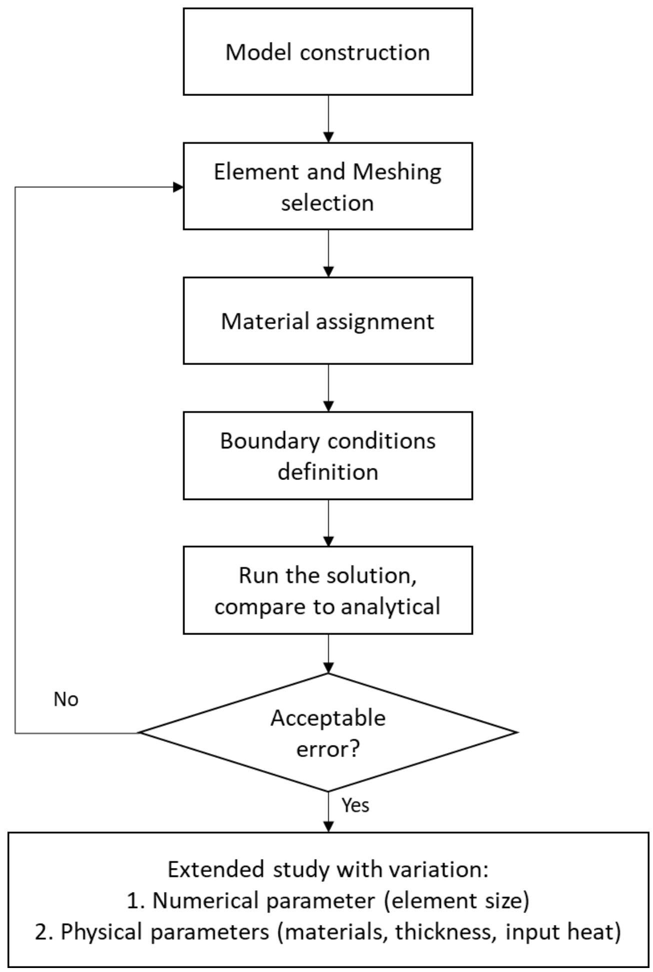
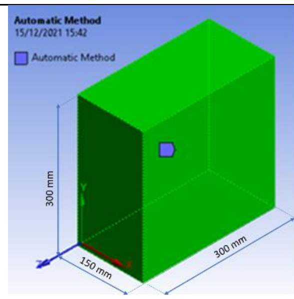
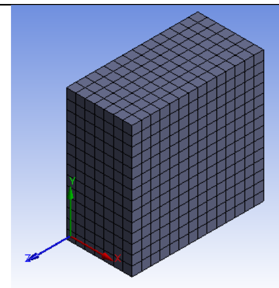
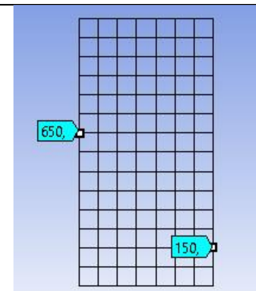


Figure 3. Methodology

The plane wall is sized 300 mm x 300 mm and has a thickness of 150 mm (L). It was initiated with ANSYS Workbench under a Transient Thermal module, a 300 mm x 150 mm X-Y plane than extruded 300 mm along the Z. An automatic method was selected since the geometry to analyze is relatively simple, and the green color confirmed that the whole body can be swept. The default element size of 22.43 mm remains unchanged, which results in 6,735 nodes and

1,372 elements. The remaining parameters, such as quality and inflation, were left as per the automatic method setup. Structural steel was selected as the material with thermal conductivity (k) of 60.5 W/m.°C. The boundary conditions were set as the temperature at the inner surface (T1 = 650 °C) and constant outer surface temperature (T2 = 150 °C).

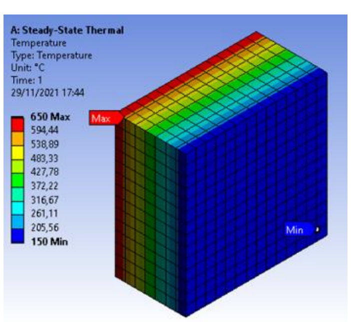
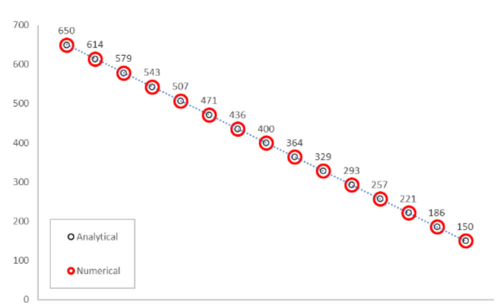
Table 1. Analysis Preparation

Geometry and Physic	Meshing	Boundary Conditions
		

RESULT AND DISCUSSION

Analytical and numerical methods were performed with the output of temperature distribution along the wall and the heat flux produced due to temperature differences across the wall. The temperature distribution as solved by heat equation based on defined boundary conditions is plotted in Table 2. The 3D contour bands describe how temperatures are distributed along the wall. The "error" will be presented in percentage (%), i.e., the value difference between numerical and analytical methods [6].

Table 2. Temperature Distribution

Temperature Distribution	Temperature Distribution Analytical vs. Numerical
	

For steady-state conditions, the heat flux ($\dot{q}$) obtained from the analytical method is 201,667 W/m2, and it is identical to the heat flux computed by ANSYS (201,670 W/m2). Therefore, the extended study can be carried on very small error (0.002%) is encountered.

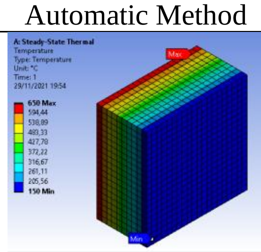
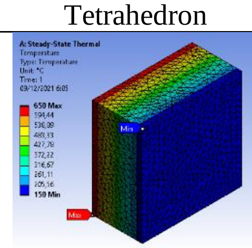
An extended study was conducted to investigate numerical and physical parameters further and understand which parameters are significant to the output. Varying element sizes and types were used to investigate numerical parameters. The wall material also varied since they had different thermal conductivity. Heat input was also studied as one of the parameters that influence the heat flux and temperature distribution. The wall thickness variations were also investigated.

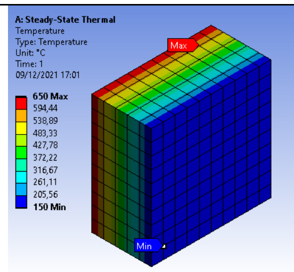
Numerical Parameter

As we know, precision computation depends somewhat on mesh properties. Good mesh quality and a prudent solution procedure will deliver an accurate result. Appropriate meshing selection must be understood since the numerical method is about approximation and iterations. Approaching a simple geometry with a coarse to medium mesh quality might be sufficient, while approximating it with a fine mesh might result in a prolonged process without significant difference. Besides, computer memory might be limited if it had to execute millions of elements. Conversely, a complex geometry might require medium to fine mesh quality to obtain better approximation with minimum errors.

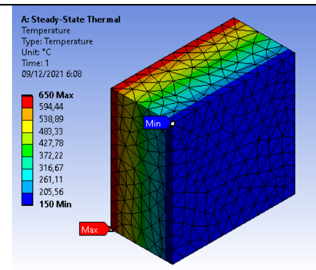
These extended studies begin with mesh variation. No "best" mesh is acceptable for any case, yet the accuracy will depend on the complexity of the analysed model [7]. Many types of mesh are available in ANSYS Fluent, where different types of mesh will provide different outputs. This study will compare an automatic meshing method to Tetrahedrons, with element variations of 15 mm, 30 mm, and 60 mm. The temperature distribution and heat flux were then compared to the analytical method.

Table 3. Meshing Methods Variation

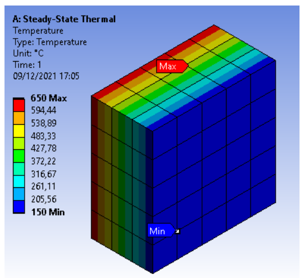
Automatic Method	Tetrahedron
	
Element Size: 15 *mm* Number of Nodes: 18,501 Number of Element: 4,000	Element Size: 15 *mm* Number of Nodes: 49,399 Number of Element: 34,276



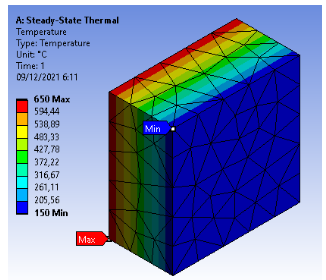
Element Size: 30 *mm*
Number of Nodes: 2,651
Number of Element: 500



Element Size: 30 *mm*
Number of Nodes: 6,926
Number of Element: 4,466



Element Size: 60 *mm*
Number of Nodes: 492
Number of Element: 75



Element Size: 60 *mm*
Number of Nodes: 1,044
Number of Element: 592

Temperature distribution output under the automatic meshing method at 15-30-60 mm element sizes were plotted in Figure 4. The temperature distribution exhibits an identical pattern to that of an analytical calculation. The computation with a 60 mm element size resulted in a 2.3% error, yet still acceptable. Indeed, 0% error was obtained with 30 mm element size and lower. Computation with a tetrahedron type of element took a longer process due to the huge number of elements compared to the automatic method. Yet, still, it gives identical heat flux and temperature distribution. Therefore, the calculation with the automatic method at 30 mm element size for this geometry had already been satisfied.

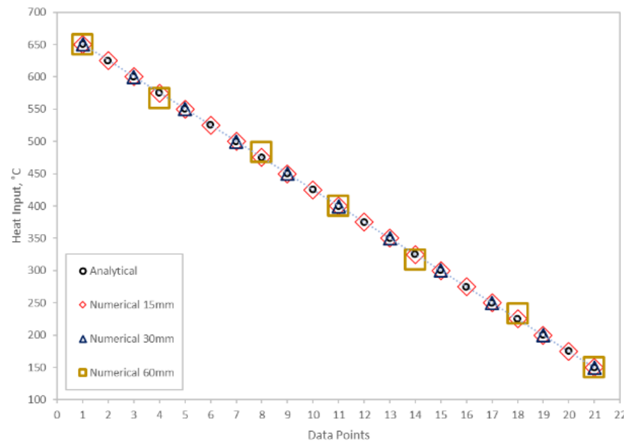


Figure 4. Temperature Distribution at Mesh Variation

The identical temperature distributions explain that the meshing method does not significantly influence this case [8]. The heat flux calculation also showed the same value regardless of the element types and sizes. It can be stated that these numerical parameters do not have a substantial impact on the heat flux and temperature distribution.

Material

In conduction, heat transfer occurs along the body of a wall. Conduction can only happen if the media has thermal conductivity, i.e., the ability to transfer heat. Thermal conductivity differs from material to material; therefore, a study was carried out to investigate how temperatures are distributed along the body of different materials and how much heat flux was produced [9].

The temperature distribution of different materials with the same operating conditions were distributed at the same spread as shown in Figure 5. The temperature distributions of all materials follow a linear pattern as depicted in Figure 6.

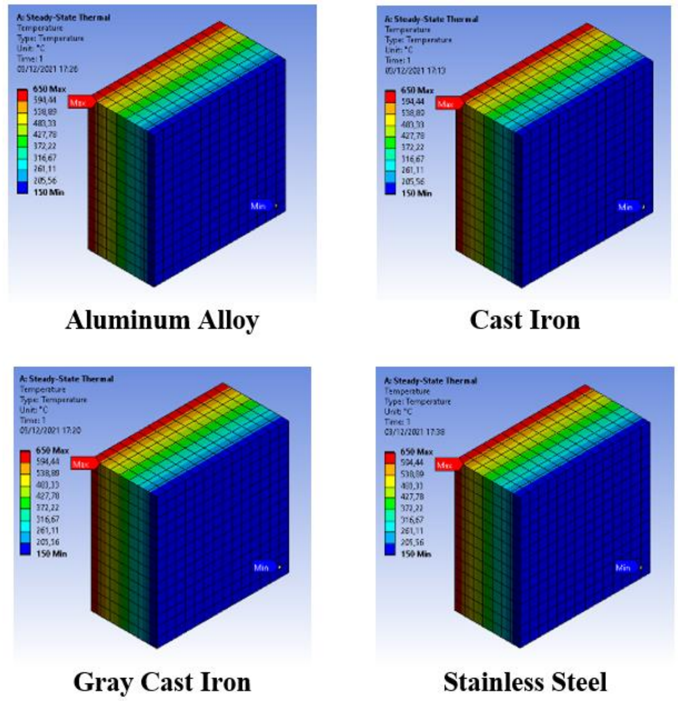


Figure 5. Temperature Distribution at Materials Variation

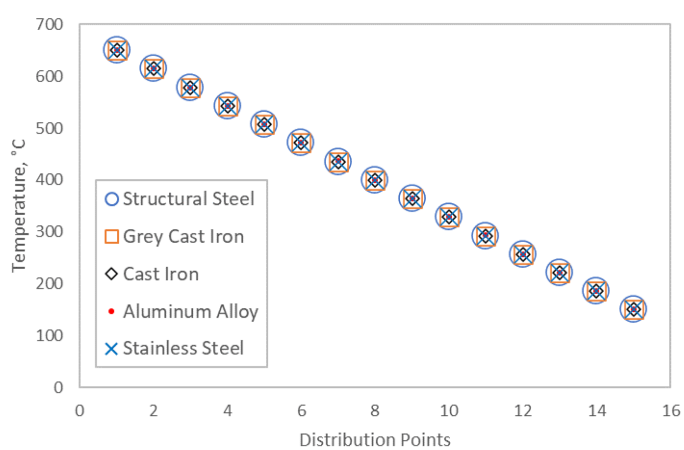


Figure 6. Temperature distribution plot at material variation

Heat fluxes of various wall materials were investigated and summarized in Table 4. The numerical and analytical comparison exhibits exceedingly minor errors, yet the method is acceptable.

Table 4. Heat Flux at Material Variation

Material	Thermal Conductivity (*W/m.˚C*)	Heat Flux (*W/m²*) Analytical	Heat Flux (*W/m²*) Numerical	Error *(%)*
Aluminum Alloy	175	583,333	582,690	+/-0,1103%
Cast Iron	83	276,667	276,670	+/-0,0012%
Structural Steel	60.5	201,667	201,670	+/-0,0017%
Gray Cast Iron	52	173,333	173,330	+/-0,0019%
Stainless Steel	15.1	50,333	50,333	+/-0,0007%

In Figure 7, thermal conductivities of the abovementioned materials were plotted against produced heat fluxes, and the pattern follows a linear equation with negligible error, with the gradient of y = 3,329x + 209.53, where y and x are respectively heat flux and thermal conductivity. Hence the equation can be rewritten as $\dot{q}$ = 3,329k + 209.53. Three other materials, i.e., Steel 1010, Iron, and Magnesium Alloy, were plotted on the graph for thermal conductivity and heat flux, and they were confirmed to adhere to linearity.

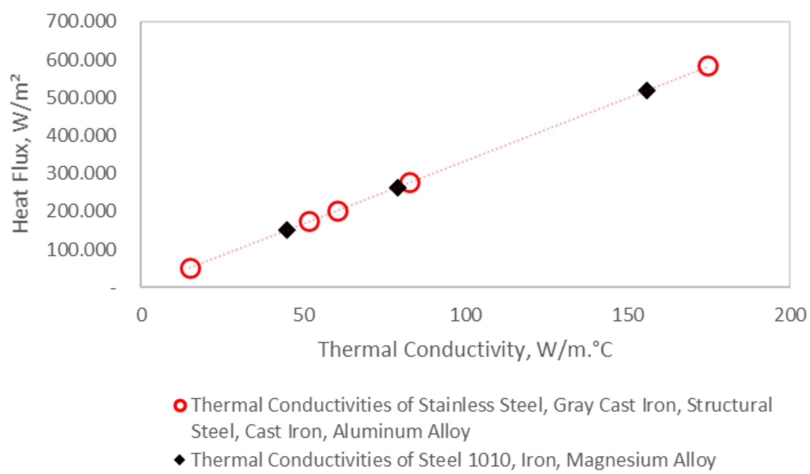


Figure 7. Heat flux vs. Thermal conductivity of various materials

Wall Thickness

Temperature distribution and heat flux along a large wall are functions of wall thickness [10]; therefore, a variation in the wall thickness is investigated to determine its significance. Wall thickness variations were studied using a 10 mm decremental from the initial geometry. The temperature bands are summarized in Figure 8. Temperature distributions agree with a linear pattern as depicted in Figure 9, although 110-120-130 mm thickness exhibits a different pattern from 140-150 mm thickness.

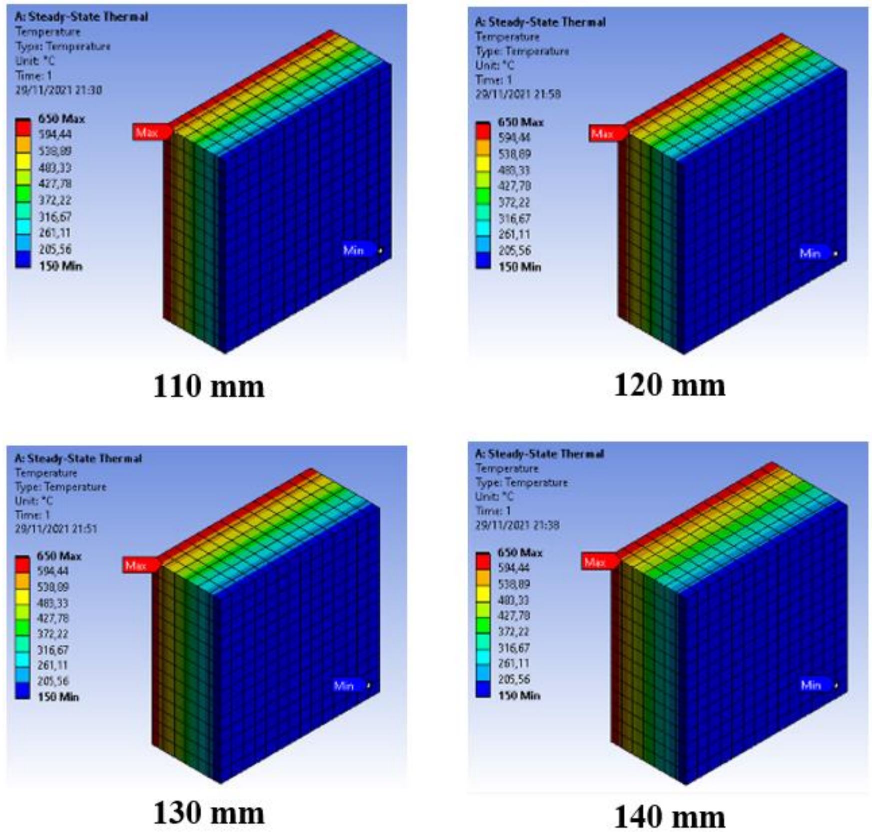


Figure 8. Temperature distribution at materials variation

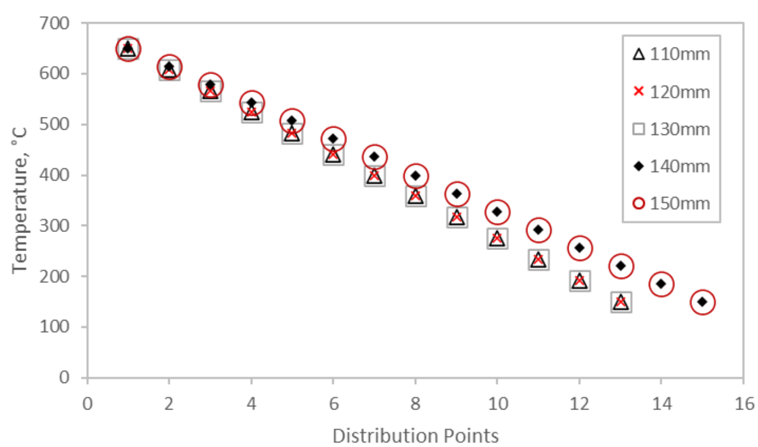


Figure 9. Temperature distribution plot at thickness variation

The comparison of heat fluxes between analytical and numerical methods from different wall thicknesses presented an insignificant error, tabulated in Table 5. Both analytical and numerical plots of heat fluxes from different thicknesses agree with the power trendline (Figure 10). The power equation of y = 500kx-1 was further explored with more variations in thickness and materials, as displayed in Figure 11, and concluded the equation of $\dot{q}$ = 500.k.L-1 can be used to predict the heat flux from the various thicknesses and thermal conductivity at constant predetermined outer wall temperature (T2).

Table 5. Heat Flux at Thickness Variation

Wall Thickness (*mm*)	Heat Flux (W/m^2) Analytical	Heat Flux (W/m^2) Numerical	Gap *(%)*
110	275,000	275,000	0%
120	252,083	252,080	+/-0.0013%
130	232,692	232,690	+/-0.0010%
140	216,071	216,070	+/-0.0007%
150	201,667	201,670	+/-0.0017%

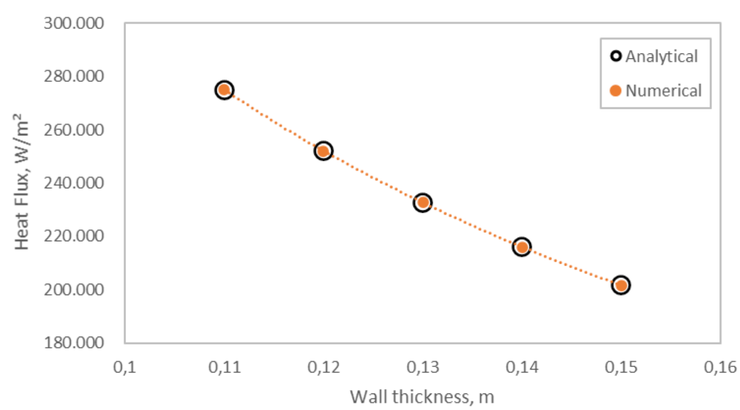


Figure 10. Heat flux plot at thickness variation

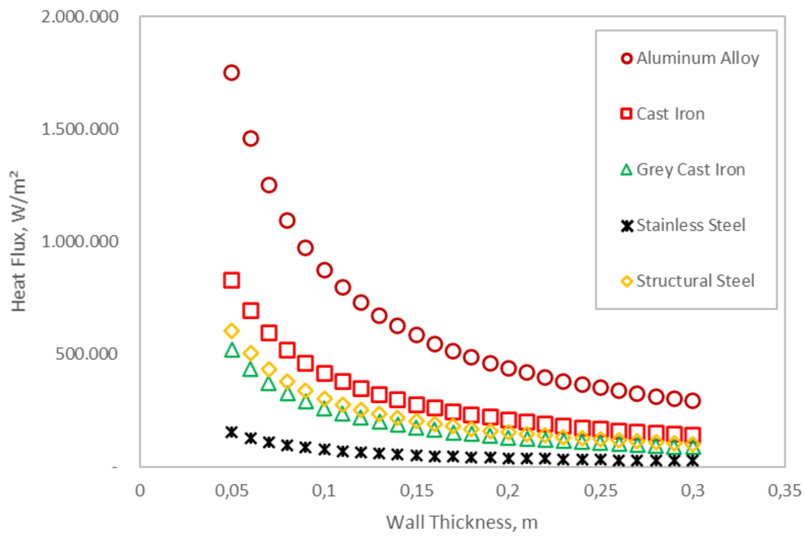


Figure 11. Heat flux plot at thickness and material variation

Heat Input

Heat exposed to the inner wall originates heat flux and temperature distribution throughout the plate. Therefore, the variation should influence the heat flux and temperature dispersal. At constant predetermined outer surface Temperature (T2), the distribution agrees with a linear pattern with variation in the slope depending on the inner surface Temperature (T1).

Table 6. Temperature Distribution at Input Heat Variation

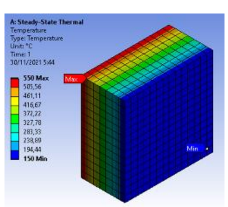
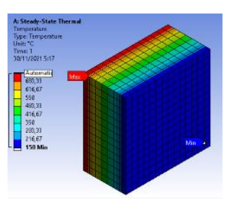
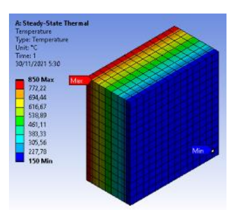
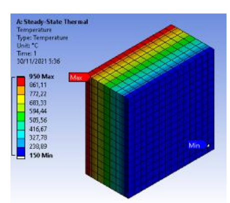
550 ˚*C*	750 ˚*C*	850 ˚*C*	950 ˚*C*
			

Table 8 presents the contour bands of temperature distribution from different heat inputs. The linearity of temperature distribution at various input heat is depicted in Figure 10.

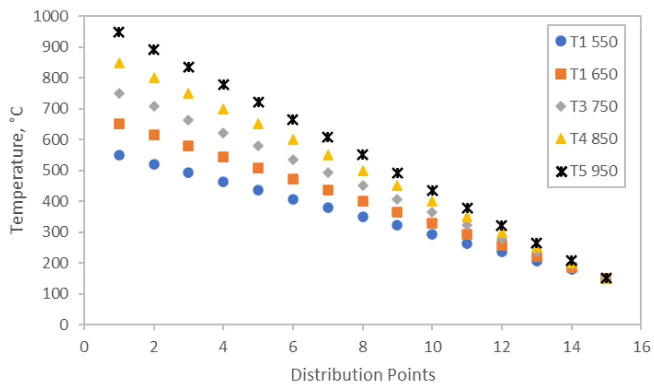


Figure 12. Temperature distribution plot at input heat variation

Heat flux is a function of temperature difference, consequently, the variation in input heat will fluctuate the generated heat flux. The heat fluxes at various input heat were analytically and numerically calculated and the comparison give a negligible error. Table 7 tabulated the comparison of both methods as well as the errors.

Table 7. Heat Flux at Input Heat Variation

Inner Surface Temperature (˚*C*)	Heat Flux (*W/m*^{2}) Analytical	Heat Flux (*W/m*^{2}) Numerical	Gap (%)
550	161,333	161,330	+/-0.0021%
650	201,667	201,670	+/-0.0017%
750	242,000	242,000	+/-0.0000%
850	282,333	282,330	+/-0.0012%
950	322,667	322,670	+/-0.0010%

Further study on the heat fluxes revealed that at fixed preset outer surface temperature (T2), input heat variations follow a linear pattern, as displayed in Figure 13. The heat flux analysis for varied materials at various input heat was carried out to determine if a relationship can be drawn regarding material and input heat to the produced heat flux. Eventually, a linear equation of $\dot{q}$ = k (6.6667 T1 – 1000) extracted from Figure 14 is introduced to predict the heat flux ($\dot{q}$) of various materials thermal conductivity (k) and input heat (T1). However, a fixed preset outer surface temperature is a condition.

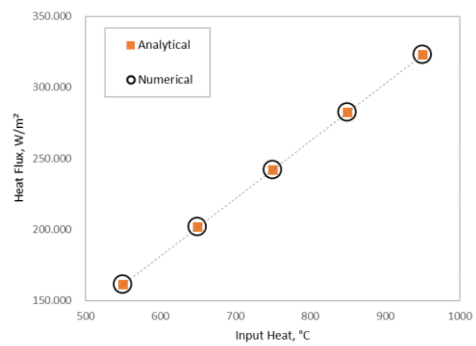


Figure 13. Heat Flux at Input Heat Variation

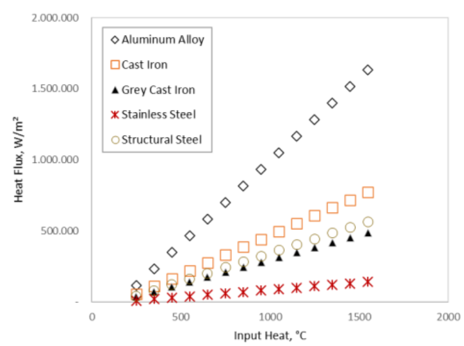


Figure 14. Heat Flux at Input Heat and Material

CONCLUSION

The thermal analysis of a plane wall showed that the comparison between analytical and numerical methods yielded an error of only 0.0017% in heat flux, confirming high accuracy in modelling. The temperature distribution from both methods was identical, further supporting this conclusion. The study also found that variations in numerical parameters, such as element size and type, had no significant effect on heat flux or temperature distribution. In contrast, physical parameters like thermal conductivity and wall thickness significantly influenced heat flux. Materials with higher thermal conductivity produced higher heat flux and variations in wall thickness and heat input directly affected the generated heat flux. The study demonstrates that heat flux can be accurately predicted under varying conditions by considering these key physical parameters.

REFERENCES

[1] DOE Fundamentals Handbook Thermodynamics, Heat Transfer, and Fluid Flow Volume 2 of 3. U.S. Department of Energy Washington, D.C. 20585. DOE-HDBK-1012/2-92 (1992)

[2] Incropera, F.P., Dewitt, D.P., Bergman, T.L., Lavine, A.S., Fundamentals of Heat and Mass Transfer. John Wiley & Sons, United States of America (2006)

[3] Bockh, P.V., Wetzel, T.: Heat Transfer Basics and Practice. Springer, Heidelberg (2012)

[4] Akin, J.E.: Finite Element Analysis Concepts. World Scientific Publishing Co. Pte. Ltd., USA (2010)

[5] Moaveni, S.: Finite Element Analysis Theory and Application with ANSYS. Prentice-Hall. New Jersey (1990)

[6] Abdelrahman, A.R., Aljibori, H.S., Al-Qrimli, H.F.: Times Three-Dimensional Spur Gear Static Contact Investigations Using Finite Element Method. Modern Applied Science Vol. 10, No. 5; DOI: 10.5539/mas.v10n5p145 (2016)

[7] Liu, Y.: Choose The Best Element Size To Yield Accurate Fea Results While Reduce Fe Model's Complexity. British Journal of Engineering and Technology Vol. 1, No. 7, pp 13-28, May 2013; ISSN: 2326 – 425X; URL: http://www.bjet.baar.org.uk, UK (2013)

[8] Deb Nath, S.K., Peyada, N.K.; Numerical Study Of The Heat Transfer Phenomenon Of A Rectangular Plate Including Void, Notch Using Finite Difference Technique. Int. J. of Applied Mechanics and Engineering, 2015, vol.20, No.4, pp.733-756. DOI: 10.1515/ijame-2015-0048, India (2015)

[9] Roy, P.K., Mallick, A., Mondal, H., Goqo, S., Sibanda, P.: Numerical study on rectangular-convex-triangular profiles with all variable thermal properties. International Journal of Mechanical Sciences 33 (2017) 251-259. http://dx.doi.org/10.1016/j.ijmecsci.2017.07.066. Elsevier (2017)

[10] Rohsenow, W.M., Hartnett, J.P., Cho, Y.I.: Handbook of Heat Transfer. McGraw-Hill Printed and bound by R. R. Donnelley & Sons Company. New York (1998).