

Research Article

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Finite element analysis of the thermal and thermo-mechanical coupling problems in the dry friction clutches using functionally graded material

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Abstract: The friction clutch is an important machine part in the torque transmission system, where it is responsible for gently transmitting the power from the engine to the gearbox and damping the tensional vibration. At the beginning of the engagement between the clutch's elements, a large amount of heat is released due to frictional sliding between the elements of the clutch system, generating very high temperatures. In this work, the two- and three-dimensional finite element models were developed from scratch to explore the clutch disk's temperature and contact pressure behaviors using an alternative frictional material such as functionally graded material (FGM). The two assumptions for the thermal loads were considered: uniform wear and uniform pressure assumptions. The thermal–structural problem for the new frictional material was solved numerically and then presented as the temperature distributions and the contact pressure at any instant of sliding time. Also, a comparison was made between the clutch system behaviors when using FGM with different frictional materials. The results showed that the FGM has superior results to the other available frictional materials.

Keywords: dry friction clutch, functionally graded material, thermal–structural problem, finite element method

Nomenclature

K	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
n_p	number of friction disks
P	pressure (N m^{-2})
q	frictional heat generated (W m^{-2})
r	radius of clutch (m)
r_i	inner radius of clutch (m)
r_o	outer radius of clutch (m)
t	time (s)
T	torque (N m)
t	slip time (s)

Greek symbols

ω_s	angular velocity at slipping period (rad s^{-1})
ε_{ij}	components of thermal strain
ν	Poisson's ratio
σ_{ij}	stress tensor (N m^{-2})
α	thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)
μ	friction coefficient

1 Introduction

The clutch's primary function is to transmit torque from the engine to the driven shaft, as well as engage and disengage the transmission system. When the friction clutch begins to engage, slipping occurs between the contact surfaces of the pressure plate, friction plate, and flywheel.

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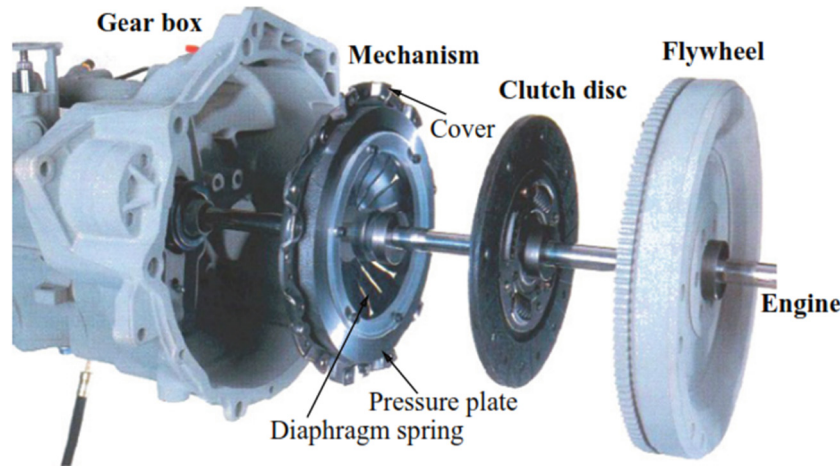


Figure 1: Main elements of the dry friction clutch system [2].

Slipping between the elements of the clutch generates heat energy on the frictional surfaces [1]. Figure 1 shows the main elements of the dry friction clutch system, which are the friction clutch disk, flywheel, and pressure plate.

A major reason for dry clutch failure is the excessive heat generation *via* sliding friction during the initial engagement, which increases the wear rate. Consequently, it changes the surface characteristics and makes the contact pressure focus on a certain zone from the nominal contact area. This change in the contact pressure will increase the heat generated several times more than in the case of normal contact pressure. So, the temperatures will increase extremely in this zone and exceed the maximum allowable temperature for the used materials. Therefore, the failure will occur on contact surfaces before the designed lifetime.

Generated heat also changes the friction characteristics of the frictional-facing material through thermal degradation, wear, and distortion of the friction disk by converting generated heat into thermal stresses. Changes in the clutch facing's friction characteristics can lead to a greater propensity to judder [3,4]. Distortion of the friction disk causes uneven contact with the pressure plate and the flywheel, resulting in localized contact pressure, hot-spotting phenomena, and thermoelastic instability [5,6]. Kinetic energy is converted into thermal energy, generating heat during the clutch engagement process. The main parameters affecting this process are the interfacial sliding speed, the applied contact pressure (clamp load), the coefficient of friction of the contacting surfaces, and the thermal properties of the materials in contact. The changes in friction characteristics with pressure and interfacial slip speed (*e.g.*, a negative gradient of the coefficient of friction with slip speed) can lead to coupling instabilities manifested in the form of judder vibrations in the vehicle [7,8]. Yang *et al.* [9]

investigated the formulation of variational principles characterizing the solutions of the coupled thermo-mechanical problem for general dissipative solids. At the same time, Bagri and Eslami [10] presented the finite element model (FEM) of generalized coupled thermoelasticity equations for a hollow disk subjected to a thermal shock. The Laplace transform method was used to transform the thermoelasticity equations. A few studies used the FEM to investigate the thermoelastic coupling behavior of clutch systems [11–16]. Chen *et al.* [17] proposed a new approach to modeling the temperature based on computational fluid dynamics simulation and decoupling technology. They used the flow-thermal bi-directional coupling method to determine the convective boundary conditions between the clutch assembly and the ambient air, improving the model's accuracy. Padmanabhan *et al.* [18] introduced an investigation of structural and thermal analysis of clutch facings with different friction materials. Clutch facings composed of base material have been modeled and analyzed in Solid Works and ANSYS Workbench. Liu *et al.* [19] modeled a numerical solution to obtain the surface temperature at different radii based on the FEM. And then, the data were compared with the experimental data. The result appears that the proposed model for estimating the surface temperature is more accurate than the conventional prediction method. Haojie and Zhaoquan [20] carried coupling field transient analysis of the clutch under continuous sliding wear conditions, and the clutch temperature change and heat generated by friction were obtained by simulation calculation under the use of simulated clutch holding for 1 s. Based on the results of the simulation, the factors that may affect the friction heat generation of the clutch are analyzed. Xie *et al.* [21] analyzed the thermal load characteristics of the dry dual clutch under the condition of multiple starting on

the ramp by software ABAQUS. The study obtains the distributions of the transient temperature field of the clutch friction pair under the conditions of multiple starting.

This article introduced two FEMs. The first model was developed to study the thermal behavior of the clutch system using a functionally graded material (FGM) disk under uniform pressure and wear assumptions. The second model was developed to find the solution to the thermo-elastic coupling problem using an FGM disk. The comparisons were made between the thermal behavior and performance of the clutch system using FGM material and the available (commercial) frictional materials (VH-03 and HDS57).

2 Finite element formulation

Transient conditions involved a time-dependent function of the heat transfer analysis. During the transient condition, the temperature change in a unit volume of material is resisted by thermal mass that depends on the mass density ρ of the material and its specific heat c . The finite element formulation can be expressed as [22]

$$[C]\{\dot{T}\} + [K]\{T\} = \{F\}, \quad (1)$$

where $[C]$ is the specific heat matrix, $\{T\}$ is the vector of nodal temperatures, $\{\dot{T}\}$ is the derivative of temperature with time ($\frac{\partial T}{\partial t}$), and $\{F\}$ is the applied heat flow [23].

2.1 Thermal problem

Elevated local temperatures caused energy buildup at contact, leading to new wear particles and subsurface fracture

propagation. Studying the slipping and heat dissipation periods is crucial to comparing the thermal behavior using different friction materials. During the sliding period, the formula calculates the heat produced assuming the uniform pressure between the contact surfaces is

$$q(r, t) = \frac{T\omega r}{n_p(r_0^3 - r_i^3)} \frac{3}{2\pi}. \quad (2)$$

However, under uniform wear conditions, the frictional heat generation during the slipping duration is equal to [24]

$$q(r, t) = \frac{T\omega}{n_p(r_0^2 - r_i^2)} \frac{1}{\pi}. \quad (3)$$

The models that represent the distribution of the frictional heat generation between the contact surfaces of the clutch's elements are shown in Figure 2.

A three-dimensional FEM (3D FEM) for the friction clutch system is very necessary to understand the complex thermal behavior displayed by clutch systems during the early engagement stages. The creation of such a FEM needs high skills and time. This model will simulate how the kinetic energy transforms into heat through contact sliding between the elements of the clutch system (flywheel, pressure plate, and clutch disk). It used two types of element types: hexahedral (hexa) and tetrahedral (tetra) to build the FEM of the clutch system.

This model overcame some challenges that faced the complexity of the geometry validity process, the parametric study, *etc.* Two types of frictional materials were analyzed using this developed FE model: FGM and commercial frictional materials (VH-03 and HDS57). The element-type “hexahedral” is chosen because it is well known

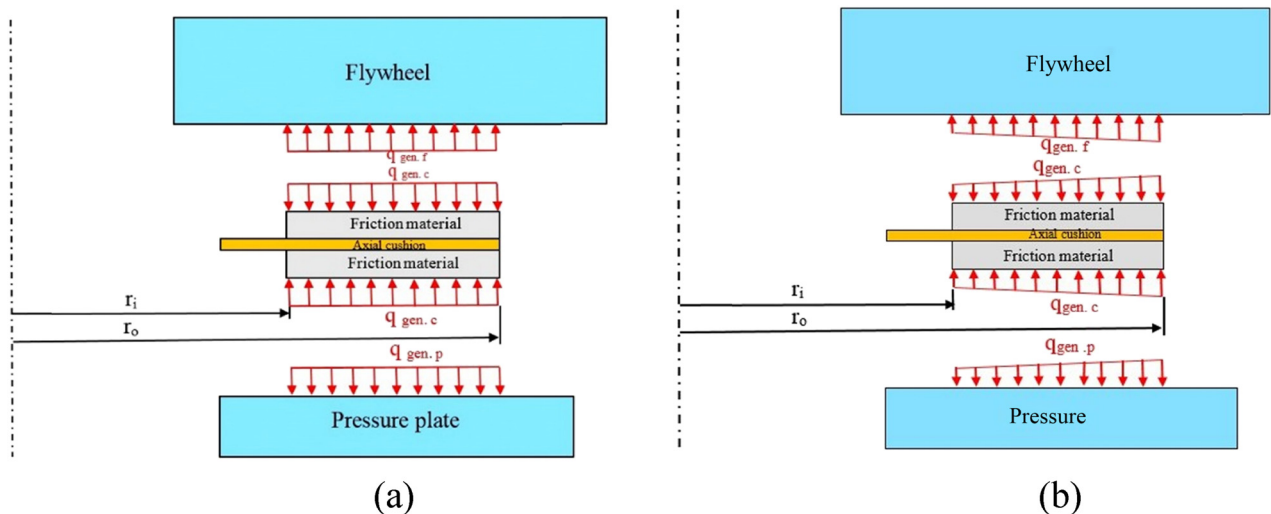


Figure 2: Distribution of the frictional heat generation between the contact surfaces of the clutch's elements: (a) uniform wear theory and (b) uniform pressure theory.

for its efficiency in representing complex geometries with mathematical stability intricacies exhibited by clutch systems. The tetrahedral element offered more flexibility when handling irregular geometries – an essential feature in simulating contact interactions and sliding among clutch elements.

The graded nature of the selected material introduces non-homogeneous thermal conduction properties, which necessitate an intricate approach to handling temperature distribution within clutch systems. However, commercial frictional materials require well-established laws for controlling contact interface behavior. These points add another level of complexity to our computational framework.

The first step was creating the three-dimensional model using SOLIDWORKS and then exporting it to the ANSYS/Workbench for numerical analysis, as shown in Figure 3. Creating a high-quality mesh for the FE model is one of the

essential steps that should be considered to guarantee simulation accuracy. Because of the complexity of the clutch system model and the symmetrical boundary condition along the circumferential direction, a sector of the whole FE model was selected to perform the numerical simulation. The grid independence tests were made to select the most suitable mesh for the FE models. Figure 4 shows the optimal meshes for the clutch system using FGM and the other frictional materials, and the results of the grid independence tests for both cases and steps of the three-dimensional model building are depicted in Figure 5. Table 1 presents the details of the element types and the numbers for elements and nodes for the developed FEMs. Table 2 lists the work conditions and material properties of the clutch's components (flywheel and pressure plate).

Two types of frictional materials are used for the frictional facing of the clutch disk in this numerical analysis.

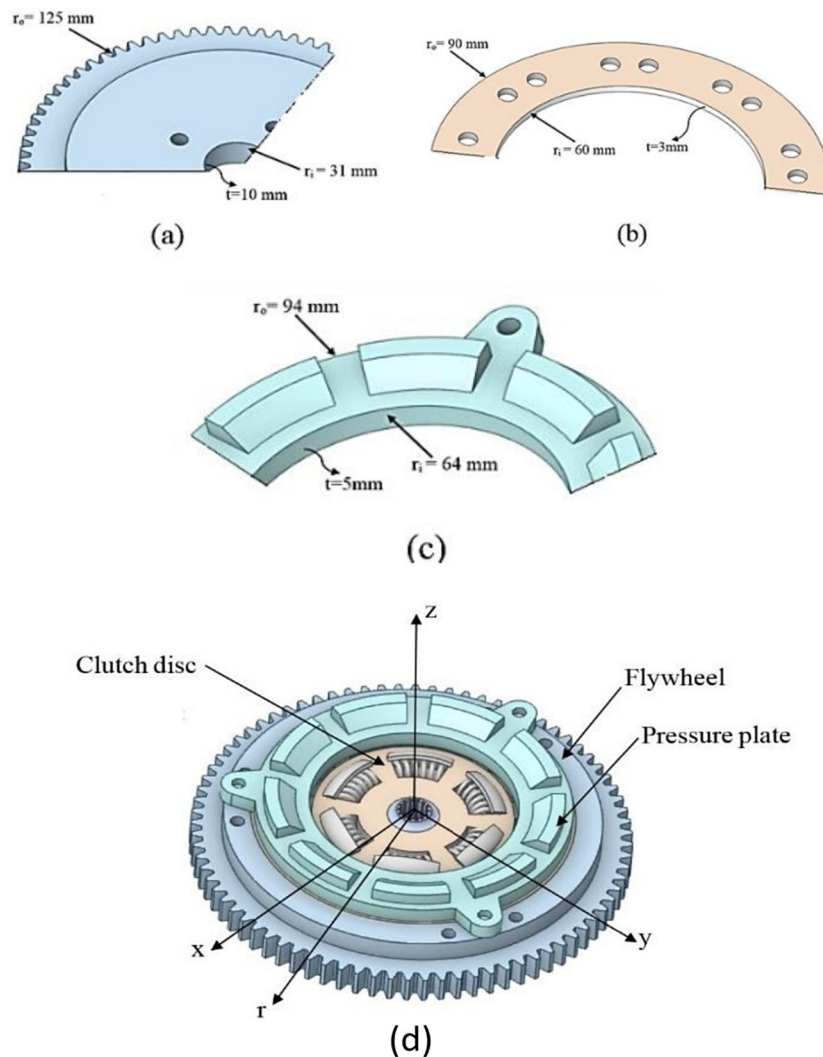


Figure 3: Dimension's clutch components: (a) flywheel, (b) friction material, (c) pressure plate, and (d) adjusted shape.

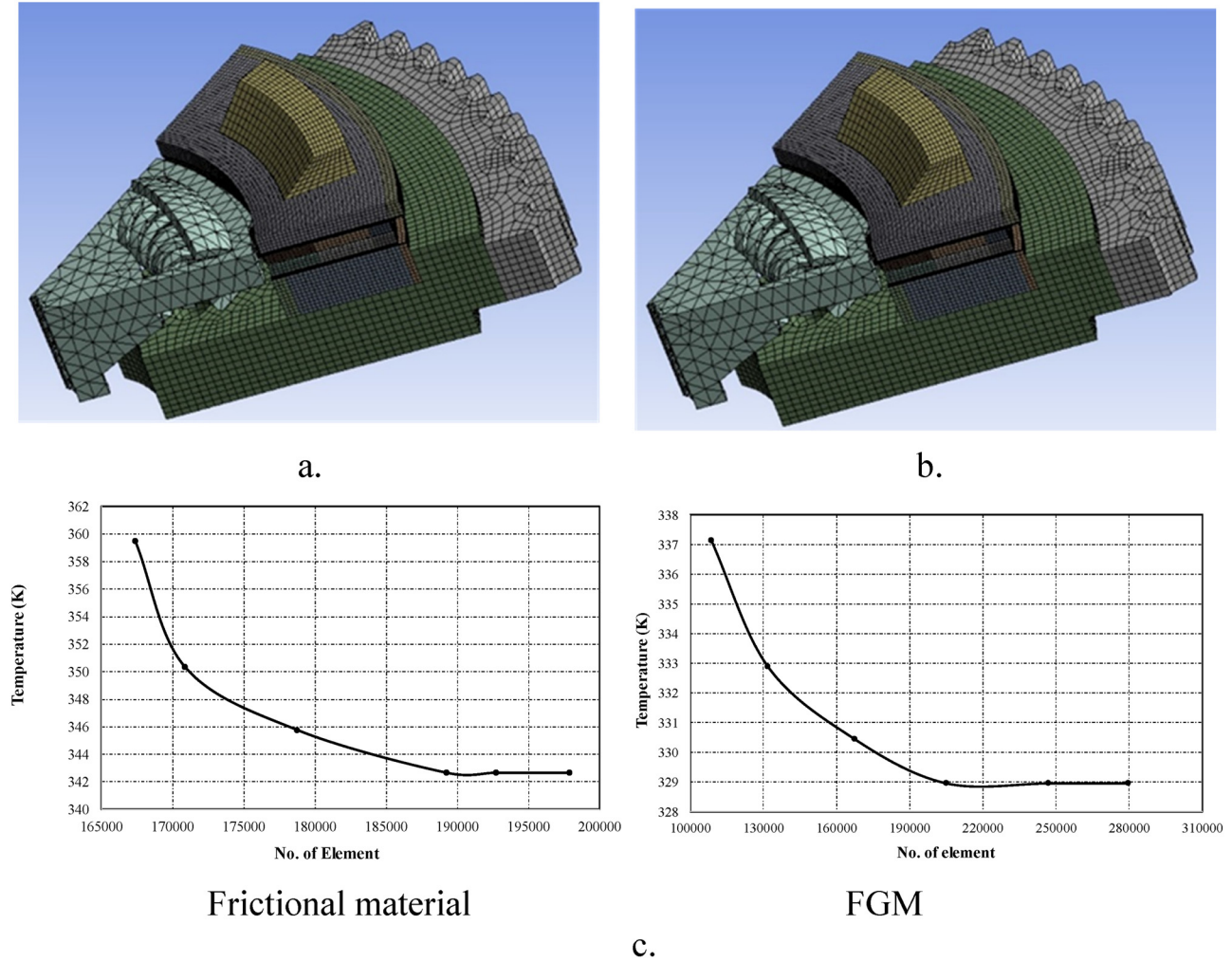


Figure 4: Optimal mesh for the clutch system using (a) FGM, (b) composite material, and (c) the grid independence tests for frictional and FGM materials.

The first one is the FGM, which consists of Sic-Al, as in the previous two-dimensional model, the number of layers is three, and the material power index (k) value is 0.5 (the layer 1 (friction layer) is 57.73% Al and 43.27% Sic), (the layer 2 (medium layer) is 81.56% Al and 18.44% Sic) and (the layer 3 (free layer) is 100% Al). The distribution of the materials for each layer is listed in Table 3 [25]. However, the second one is the commercial frictional materials VH-03 and HDS57; their properties are listed in Table 4.

2.2 Thermo-mechanical problem

The combination of engineering examinations and physics analysis is used to address engineering design issues involving thermal and thermoelastic models. The thermal-mechanical coupling analysis involves a single FE environment

constructed independently, enabling the identification of the coupled material physics solution [26]. The simulation addresses the thermo-elastic problem of contact pressure by analyzing the temperature field and using Hook's law solution, addressing two coupled issues simultaneously [27]:

$$\varepsilon_{ij} = \frac{(1-\nu)}{E} \sigma_{ij} - \left(\frac{\nu}{E} \sigma_{mm} + \alpha \bar{T} \right) \delta_{ij}, \quad (4)$$

and the equation of the equilibrium is

$$\frac{\partial \sigma_{ij}}{\partial x_{ij}} = 0. \quad (5)$$

In order to compute the friction-generated heat, it will use elastic analysis to find the contact pressure and apply thermal load in the transient heat conduction model. Then, determine the thermal stresses using the temperature distribution and analyze the new temperature distribution if the following equation holds:

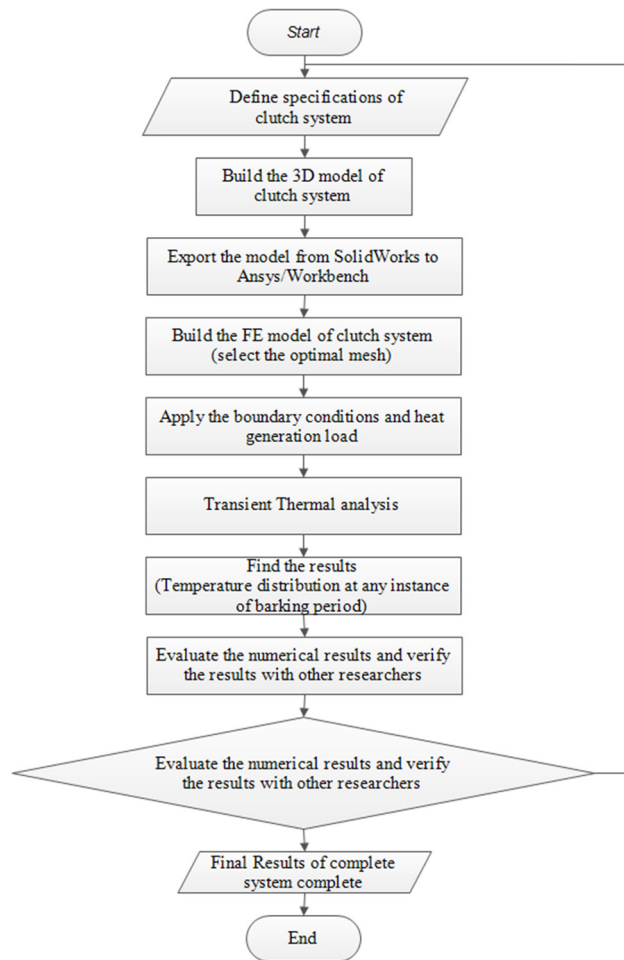


Figure 5: Flowchart to build the 3D FEM for the clutch system.

Table 1: Mesh properties

Material	FGM	Frictional materials
Element type	Hexa + tetra	Hexa + tetra
Nodes number	1097469	848652
Element number	204956	189242
Skewness	7.0968×10^{-2}	6.1768×10^{-2}

$$\nabla^2 \bar{T} = \frac{1}{\alpha} \frac{\partial \bar{T}}{\partial t}. \quad (6)$$

Figure 6 shows the main steps used to conduct the numerical analysis, including elastic contact, to find the thermal stresses and pressure distribution. In addition, the transient thermal investigation for temperature distribution during heating operation was made [28].

The other assumptions of the FE model can be listed as follows:

When two surfaces (1 and 2), as shown in Figure 7, are in the contact state [29]:

$$P > 0 \rightarrow \omega_1 = \omega_2 \rightarrow \bar{T}_1 = \bar{T}_2, \quad (7)$$

where

$$q = \mu P \omega r = -\sum q_{\text{two surfaces}} = -(q_1 + q_2). \quad (8)$$

Two surfaces (1 and 2) are adiabatic when there is no contact between them:

$$P = 0 \rightarrow q = 0 = q_1 = q_2. \quad (9)$$

The two-dimensional axisymmetric FE model can be used, as shown in Figure 8, and restricting the flywheel's backside in the elastic model is illustrated in Figure 9. The PLANE55 element type was chosen for the thermal FEM. This element has four nodes, and its temperature is thought to be its lone degree of freedom. In contrast, the coupling issue in the clutch model is represented by the PLANE13 element in the elastic FEM. Up to four degrees of freedom are available to this type of element. Additionally, each element has four nodes, the same number as the element chosen for the thermal problem. There are three levels of flexibility in the case problem. Temperature and radial and circumferential deformations are these degrees of freedom. The Conta172 element is used for the frictional contact surfaces.

Figure 10 shows the validation of current numerical solutions with experimental approaches by Nasr *et al.* [30]. The match ratio of maximum surface temperature during the sliding process reached more than 94.8%. Deviations from the experimental curve appeared, and this is mainly due to the fact that, in numerical analysis, it is assumed that the exchange of heat occurs between the lining and its surroundings on the borders of contact; hence, lower temperatures occur at the lining of these sites. This is also due

Table 2: Flywheel and pressure plate's work conditions and material properties [26]

Parameter	Value	Parameter	Value
Density for pressure plate, flywheel, and axial cushion [kg m ⁻³]	7,200	Specific heat for pressure plate, flywheel, and axial cushion [J kg ⁻¹ K ⁻¹]	400
Conductivity for pressure plate and flywheel [W m ⁻¹ K ⁻¹]	56	Initial temperature [K]	300
Maximum angular slipping speed [rad s ⁻¹]	555	Torque [N m]	176

Table 3: Material properties of Al and Sic materials

Material	Al	Sic
Friction coefficient	0.47	0.6
Specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)	923.5	750
Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	160	120
Density (kg m^{-3})	2,770	3,100

Table 4: Material properties of VH-03 and HDS57 materials

Material	VH-03	HDS57
Friction coefficient	0.42	0.53
Specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)	1,378	1,364
Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	0.33	0.23
Density (kg m^{-3})	1,950	1,700

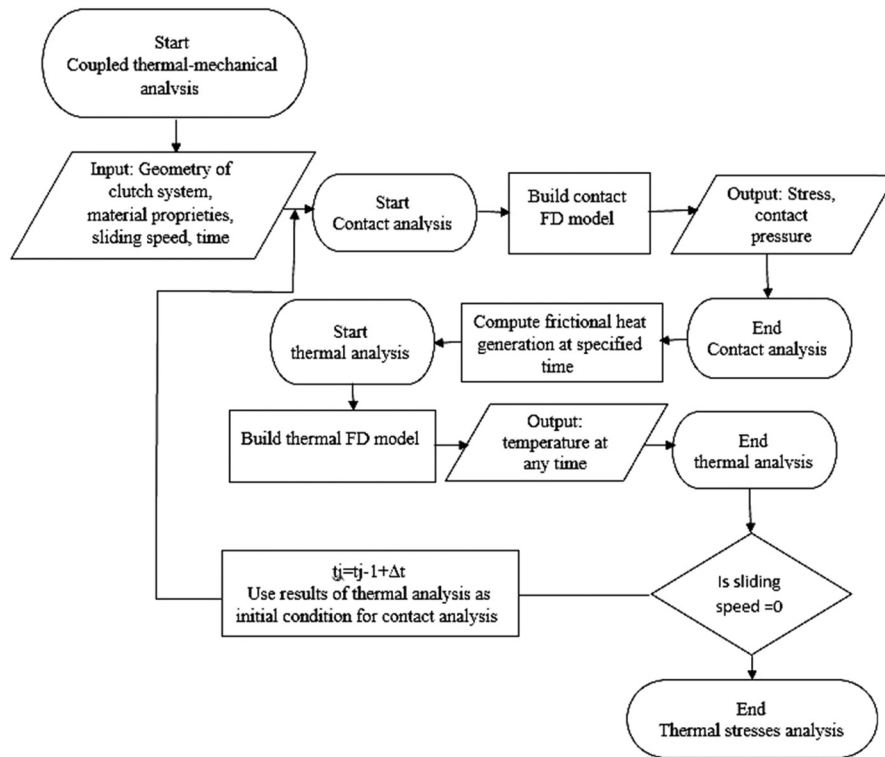
to the violent fluctuations of the frictional torque at the end of the engagement process. The parameters of analysis were 1,200 rpm speed and 4.5 kg m. From an engineering application perspective, the validity of the numerical model was validated with an experimental approach.

3 Results and discussions

This section will present the most important results obtained using the developed FEMs (2D and 3D) for analyzing the thermal and thermal-elastic behaviors of the friction clutch system during the engagement period using different friction materials. The results highlighted the behavior of the clutch system using the FGM as an alternative friction material.

Figure 11 shows the variation of maximum surface temperatures using the FGM clutch disk under different uniform wear and pressure conditions, with a slip period of 0.4 s. It can be noted that the thermal effect on the clutch system increased dramatically under the uniform pressure assumption compared with the uniform wear assumption at any time in the sliding period. The temperature difference between the two cases grew at any instance period until the halfway point of a sliding period when the highest temperatures occurred. After this point, the temperature difference diminished until the sliding time was over.

Figures 12 and 13 illustrate the variation of maximum temperatures using different friction materials under uniform pressure and wear assumptions. FGM showed excellent thermal behavior compared with the other frictional

**Figure 6:** Flowchart of the numerical simulation of the coupled thermoelastic problem.

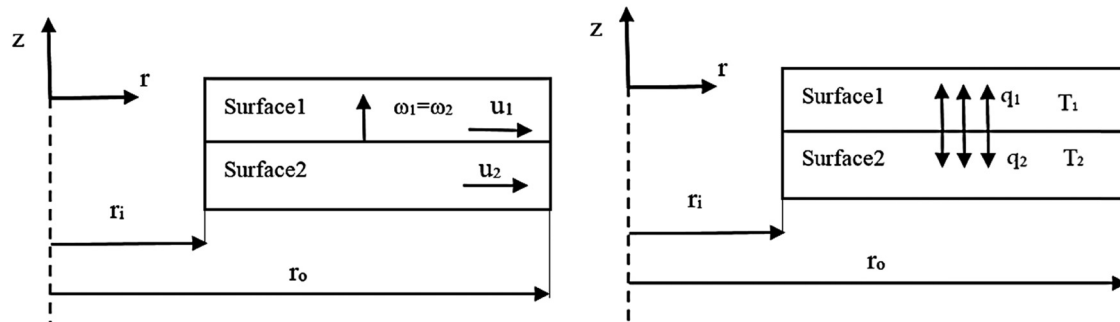


Figure 7: The Contact model for the clutch system.

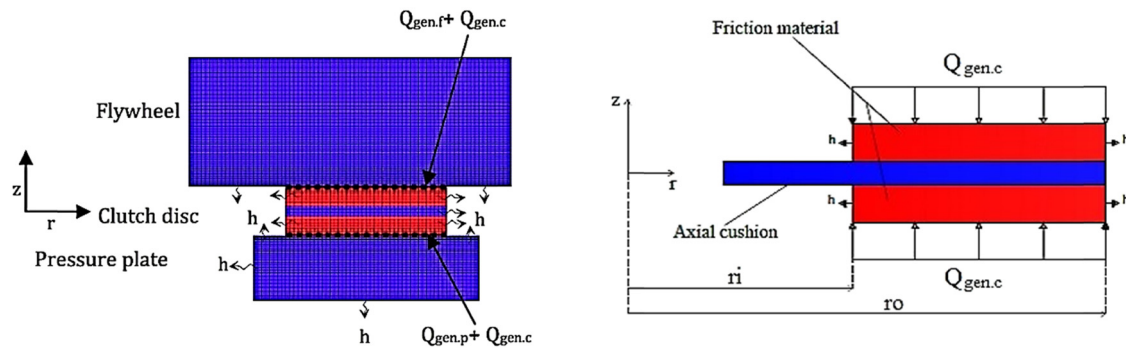


Figure 8: FE models of dry clutch components with the boundary conditions.

materials. The FGM has better characteristics to dissipate heat (e.g., at 1 s) compared to the VH-03 and HDS57 materials under both assumptions. This result is due to the good thermal properties of the FGM material, which lead to an increase in the rate of heat transfer by conduction and finally a lower surface temperature within the allowable limit.

Figure 14 presents the temperature distribution of the clutch system using the 3D FEM using FGM under uniform pressure and uniform wear assumptions. These results were captured when the highest surface temperature value occurred ($t_s = 0.2$ s) during the engagement.

The second part introduced the variation of the maximum contact pressure between the contacting elements

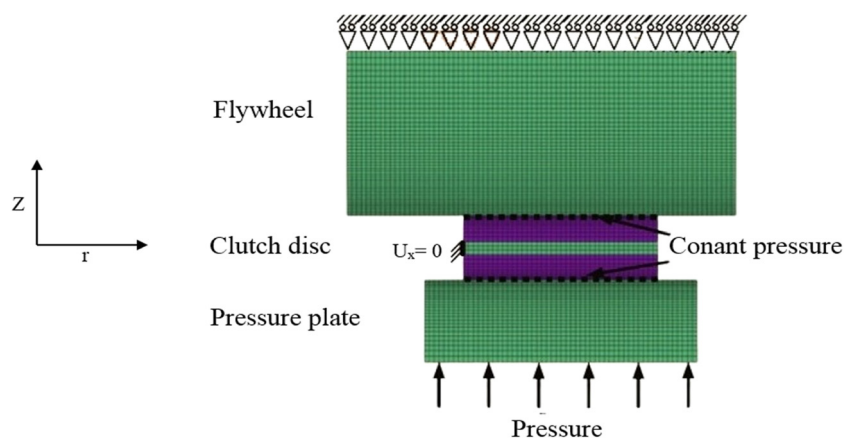


Figure 9: FE model of elastic problem with boundary conditions.

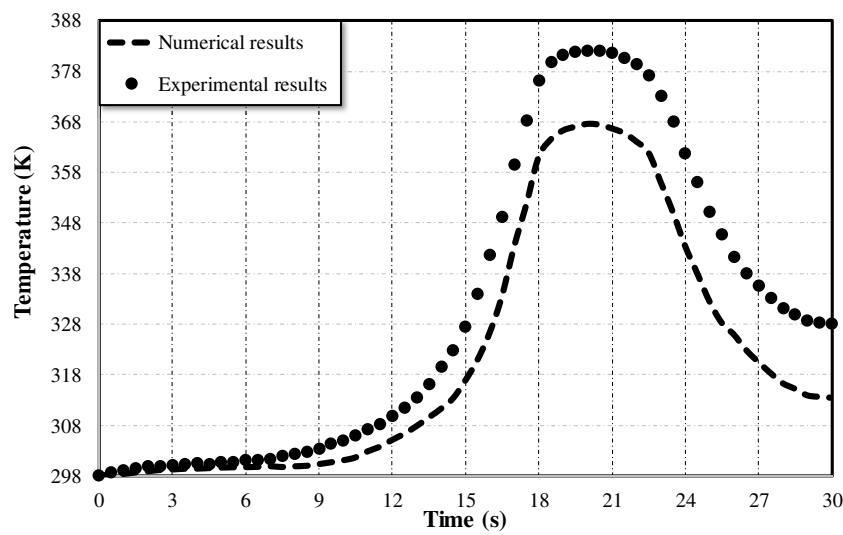


Figure 10: Comparison between numerical and experimental results.

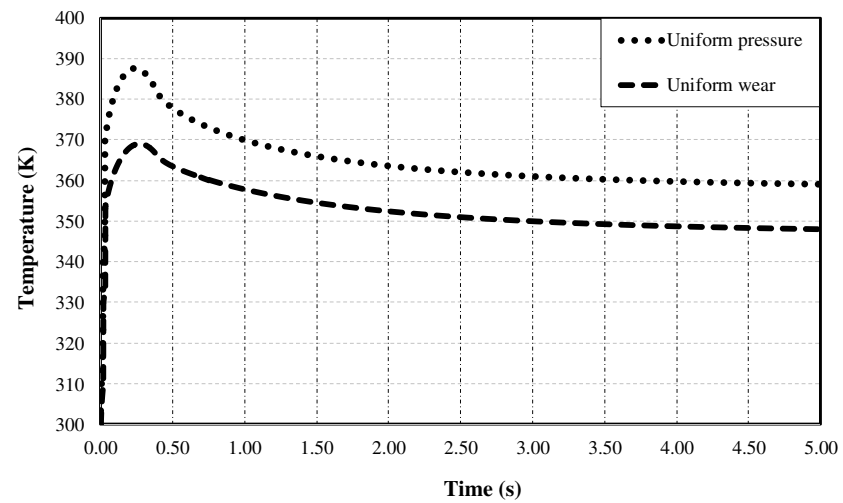


Figure 11: Variation of maximum temperatures using FGM clutch disk under different conditions.

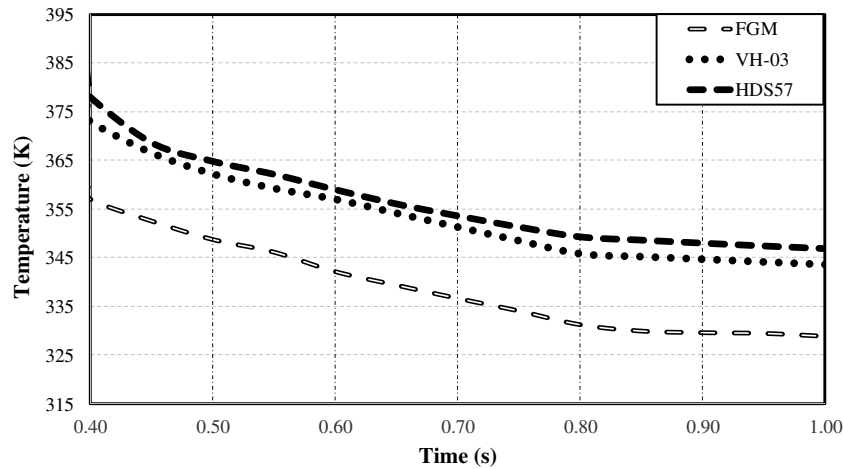


Figure 12: Variation of maximum temperature using different friction materials under uniform pressure assumption.

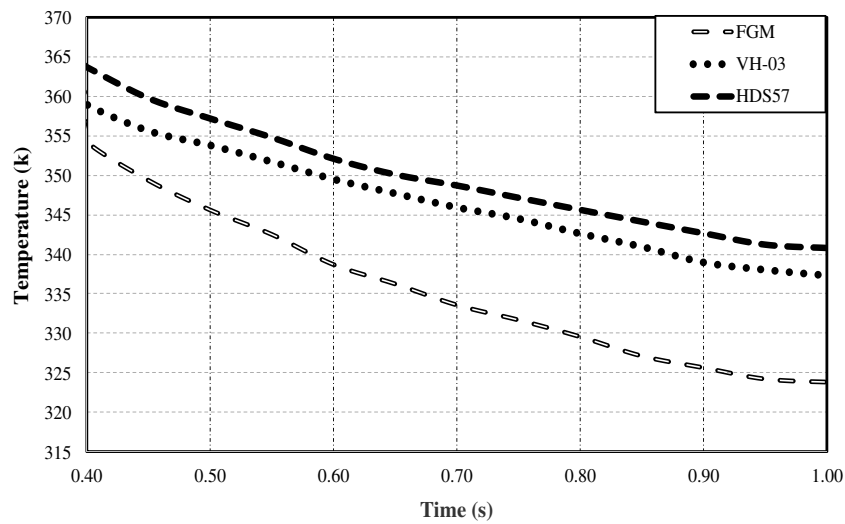


Figure 13: Variation of maximum temperature using different friction materials under uniform wear assumption.

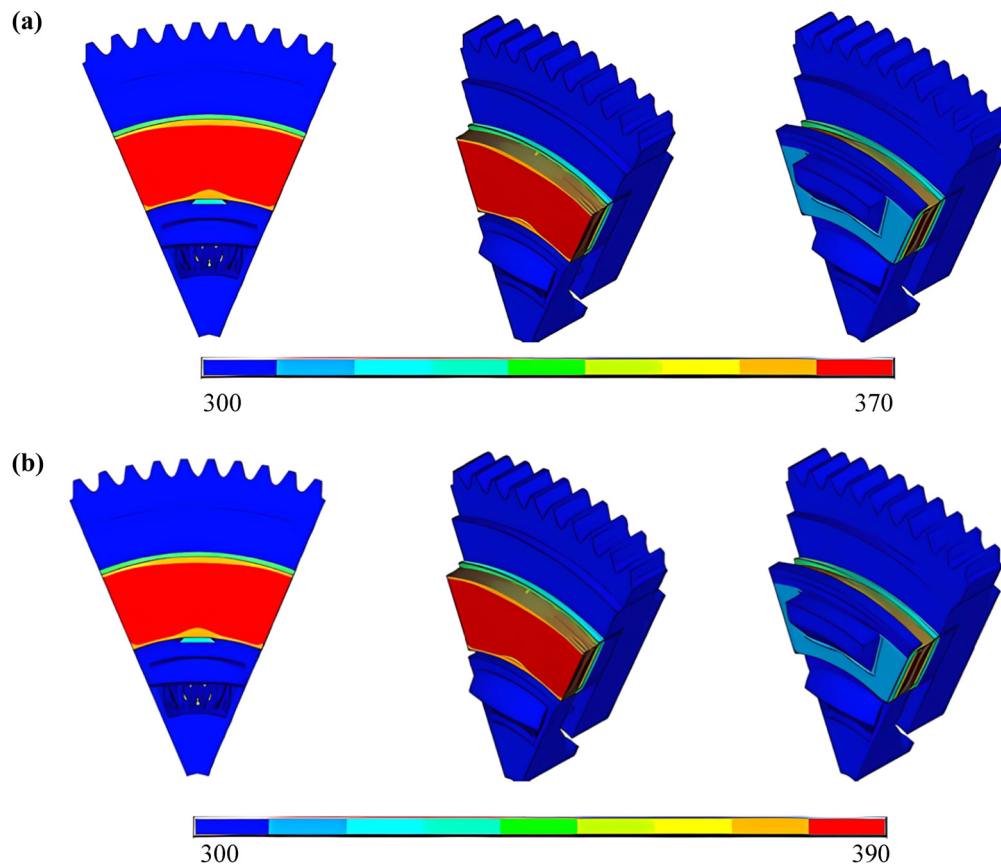


Figure 14: Temperature distribution of the clutch system using FGM at 0.2 s under (a) uniform wear and (b) uniform pressure.

(clutch disk and pressure plate, clutch, disk, and flywheel) under the uniform pressure assumption using different frictional materials.

Figures 15 and 16 demonstrate the variation of the maximum contact pressure on clutch surfaces between the clutch disk and pressure plate and between the clutch

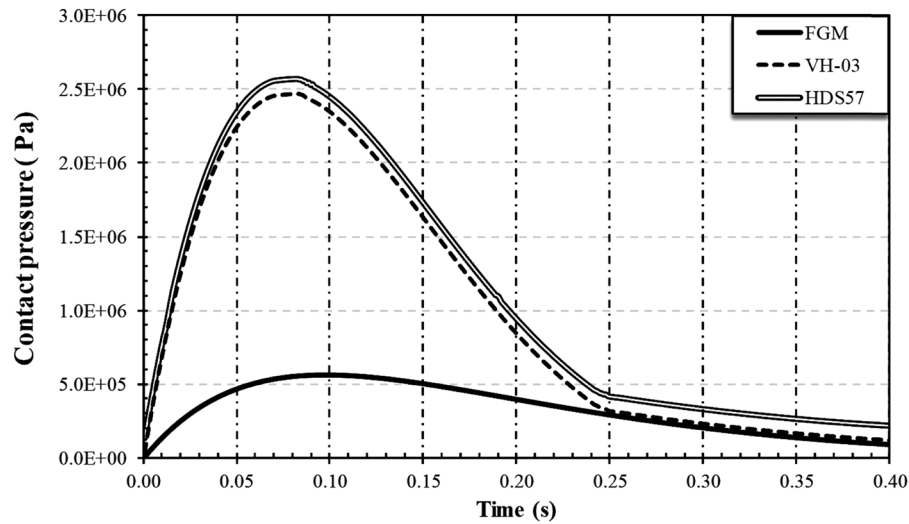


Figure 15: Variation of maximum contact pressure on the pressure plate side during the slip period at the interface.

disk and flywheel during the slipping time using different friction materials. It can be seen that the values of the contact pressure on the pressure plate side are higher than those on the flywheel side when using the VH-03 and HDS57 friction materials. However, it obtained approximately the same level of contact pressure for both sides (pressure plate and flywheel) when using the FGM friction material. The maximum values of the contact pressures when using the FGM on the flywheel and pressure plate sides are found to be 0.559 and 0.56 MPa, respectively. It can be observed that the behaviors of the contact pressure are approximately similar when using the VH03 and HDS 57 friction materials. On the other hand, it is very clear that the level of contact pressure decreased remarkably when using

the FGM material instead of the other friction materials. The reductions in the contact pressure were approximately 77 and 78% when using the FGM material instead of the VH-03 and the HDS-57 materials.

4 Conclusions and remarks

This research article spotlights the numerical solutions to the thermal and thermo-mechanical problems of the dry friction clutch during a single engagement. Axisymmetric and 3D FEMs were built to represent the numerical simulation of the clutch system during the beginning of the engagement

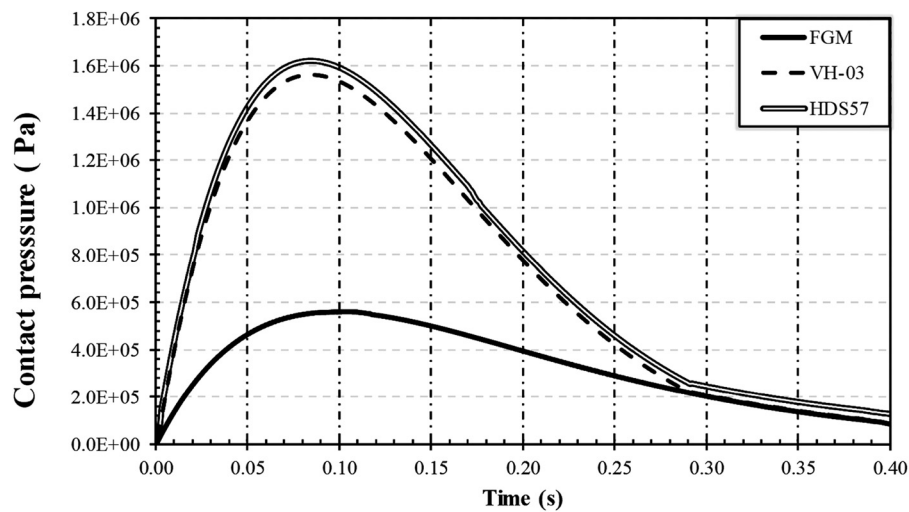


Figure 16: Variation of maximum contact pressure on the flywheel side during the slip period at the interface.

(sliding phase). The effect of using different frictional facings (FGM, HV-03, and HDS57) on the thermal performance of the clutch system was examined deeply. Based on the obtained results, it can be summarized as follows:

Clutch disk surface temperatures increase under uniform pressure higher than under uniform wear during sliding phases. When slip time is short, the difference between them grows until the maximum temperature occurs (in this case, the midtime of the sliding period). Then, the difference between them decreases very slowly. The results proved that using FGM enhanced the improvement of the thermal behavior of the friction clutch system, as the level of temperatures decreased due to the good thermal properties of this material compared to the currently available commercial friction materials. The heat dissipation rate has increased dramatically due to the high thermal conductivity of the FGM compared to the other friction materials. The other important point directly connected to reducing the generated heat level is the value of the contact pressures, where the frictional surfaces made of FGM material showed lower contact pressure (approximately 77%) compared to the VH-03 and HDS57 materials. The new 3D FEM is considered a promising numerical tool that can be used to investigate many complex problems in the future, such as asymmetric thermal load, surface roughness, hot spots, and flash temperature.

The novel point of this research work is to build a numerical model based on the FEM that is capable of overcoming the difficulties and obstacles faced by the previous models for analyzing the performance of the frictional clutch systems during the period of sliding and under the influence of thermal and structural loads. This developed model can find the temperature distributions at any moment during the sliding period, as well as find the stresses to which the friction system is exposed. Another point worth noting is that this 3D numerical model for the friction clutch system includes all the complexities of geometries of each part of the friction system. This developed model can be used to find the solution to the coupling problem (thermal and structural) at the same time and overcome the obstacles facing previous models, such as the possibility of studying and analyzing other important problems that were difficult to study previously, such as the wear, surface roughness, special friction material (*e.g.* FGM), and asymmetric load problems.

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NAJ: methodology, formal analysis, investigation, writing – review & editing. IYH: Formal analysis, funding acquisition, resources, writing – review & editing. OIA: Investigation, project administration, writing – review & editing. MNM: Investigation, writing – review & editing, validation.

Conflict of interest: Authors state no conflict of interest.

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