Serbian Tribology Society

SERBIATRIB '19

16th International Conference on Tribology

Faculty of Engineering
University of Kragujevac

Kragujevac, Serbia, 15 – 17 May 2019

THREE-DIMENSIONAL SIMULATION OF THE THERMAL PROBLEM IN FRICTION CLUTCHES USING FINITE ELEMENT TECHNIQUE

Laith A. SABRI[1], Josef SCHLATTMANN[2], Oday I. ABDULLAH[3,2]*
Nesser Eddine BELIARDOUH[4], Emilia ASSENOVA[5]
[1]Case Western Reserve University, USA
[2]Hamburg University of Technology, Hamburg, Germany
[3]University of Baghdad, Baghdad, Iraq,
[4]Badji Mokhtar University of Annaba, Annaba, Algeria
[5]Society of Bulgarian Tribologists, Sofia, Bulgaria
*Corresponding author: oday.abdullah@tuhh.de

Abstract: *This research paper presents a new numerical model of the single disc clutch that works under the dry conditions, whereas this model simulates the actual model in terms of geometry. It was overcome the difficulties that which faced the researchers in the previous literatures to build the three dimensional model of friction clutch. It was investigated deeply the thermal problem that occurred during the sliding period when the friction clutch starts to transfer the torque. In this paper, the finite element technique was applied to implement the thermal analysis. The developed finite element model was verified by comparing the obtained results with results of the other researchers that used different approaches. Moreover, the influence of the sliding speed on the thermal behaviour of the clutch disc has been studied.*

Keywords: *Dry friction, friction clutch, thermal problem, finite element method*

1. INTRODUCTION

The main resource of the failures and damages in the contacting surfaces and the reduction in the performance of the automotive brakes and clutches can be attributed to the excessive temperature that will be appeared during the first stage of engagement due to the sliding between the contacting parts. These excessive temperatures will be leaded to produce high thermal stresses. These stresses are considered the main reason to appear the cracks and the permanent deformations in the surfaces of the element of clutch system. Finally, these blemishes will be reduced the lifetime of the friction clutch system. In order to reduce the percentage of clutch failure before expected lifetime, it should be find out the distributions of temperatures during the engagements and what are the effective factors on the thermal problem of the friction clutches during the early stage of engagement. It can be seen the main parts of the friction clutch disc that are responsible to transfer the torque from engine to gearbox in Figure 1.

Most of researchers investigated numerically the friction clutch system were they used the two dimensional models (axisymmetric) to obtain the thermal behaviour during the sliding period. They overcame the complexities of the clutch geometry by reduce the thermal problem from three dimensions to the two dimensions. It was obtained the distributions of temperature and contact pressure with an acceptable degree of accuracy [1-12].

While the other researchers who obtained the analytical solution, the supposed some assumptions to reduce the complexities of the problem. One of these assumptions is to reduce the thermal problem from three-dimension problem to the one-dimension problem. Because of the difficulties to obtain the analytical solution in the two-dimension or three-dimension [13-24].

On the other hand, the experimental solution as we know it is very expensive as well it takes a long time to build any test rig device. Therefore, the numerical solution among all available solutions is considered the most suitable to reduce the time and cost of computations, this is in case where the mathematical model was built in the right way taking into consideration the influence of all effective factor on the system under working conditions.

The aim of this research is to develop a new solution based on the approximation approach (finite element method) of the thermal problem in the dry friction clutches that appeared during the sliding. Whereas, the developed approach in this work takes into account all the complexities of geometries that are existing in the clutch parts. The results present the temperatures distributions of all elements of the clutch system in the whole period of sliding of a single engagement.

2. STATEMENT OF THE PROBLEM

Through the early period of engegement (sliding period, $0 \le t \le t_s$), most kinetic energy will be transferred into heat. In this research paper, It has been supposed that all friction energy will be consumed and will be converted into heat energy. It can be written the form of total frictional heat generated during the sliding as follows [9],

$$Q_t\,(r,t) = \mu\, p V_s; \quad 0 \le t \le t_s \qquad (1)$$

Where, $V_s = \omega_s\, r$

V_s: Sliding speed

ω_s: Angular sliding speed [rad/sec].

It was assumed that the angular sliding speed decrease linearly with time as following,

$$\omega_s(t) = \omega_o(1 - \frac{t}{t_s}), \quad 0 \le t \le t_s \qquad (2)$$

ω_o: Initial angular sliding speed of the friction clutch (t_s=0).The frictional heat generated on the surfaces of clutch disc at any instant of sliding is,

$$Q_c\,(r,t) = f_c\, \mu\, p\, r\, \omega_o(1 - \frac{t}{t_s}); \quad 0 \le t \le t_s \qquad (3)$$

f_c: Heat partition factor that determine the amount of frictional heat which enter into the clutch disc, pressure plate and flywheel.

It has been assumed that the materials of the pressure plate and flywheel are the same, therefore the heat partition factor is [12]

$$f_c = \frac{\sqrt{K_c\ \rho_c\, c_c}}{\sqrt{K_c\ \rho_c\, c_c} + \sqrt{K_f\ \rho_f\, c_f}} = \frac{\sqrt{K_c\ \rho_c\, c_c}}{\sqrt{K_c\ \rho_c\, c_c} + \sqrt{K_p\ \rho_p\, c_p}} \qquad (4)$$

K: thermal conductivity

ρ: Density

c: Specific heat.

It was indexed all parameters of the axial cushion with *cu*, friction material with *c*, flywheel with *f* and pressure plate with *p*.

The difference in speeds between the flywheel and the pressure plate from one side and the friction clutch disc from the other side will lead to generate a high amount of frictional heat. The heat dissipation will be occurred by conduction between the parts of the clutch system and by convection to the surrounding environment. The time of the sliding of the friction system is very short, therefore the effect of radiation is ignored.

The first step is to build the geometry (three-dimensional) of the clutch system based on the real dimension by using Solidworks2018. The next step is to export the model of the clutch system to Ansys/workbench 18 to find the results of the thermal problem.

It can be written the parabolic heat conduction equation in the cylindrical coordinate system to find the temperature field of the friction clutch components as following (Fig. 2):

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (5)$$

r: Radial coordinate [m]
ϑ: Circumferential coordinate [rad]
z: Aaxial coordinate [m]
α: Thermal diffusivity (*α*=*k*/*ρ c*)

On the exposed surfaces of the friction clutch models, the convection takes place. It was assumed that the coefficient of heat transfer is independent of temperature. The boundary conditions and initial conditions of the case study of the friction clutch are shown in Figure 3. The initial temperature is,

$$T(r,\theta,z,0)=T_i \quad (6)$$

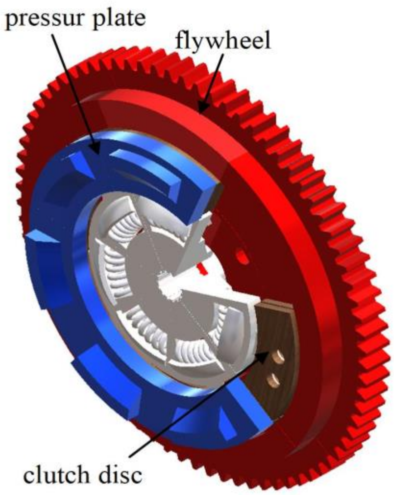

Figure 1. The main components of the frictional clutch system

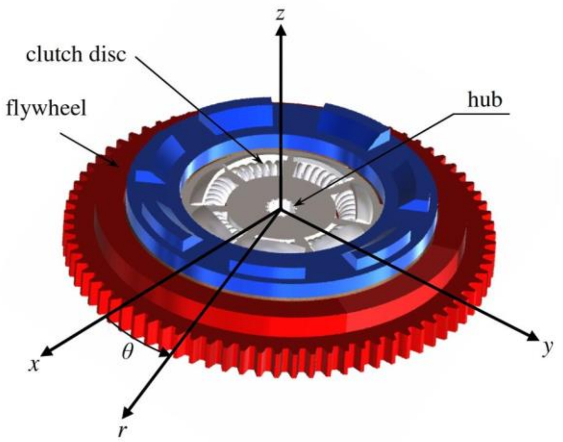

Figure 2. Three-dimensional model of frictional clutch system

(single-disc with two effective faces)

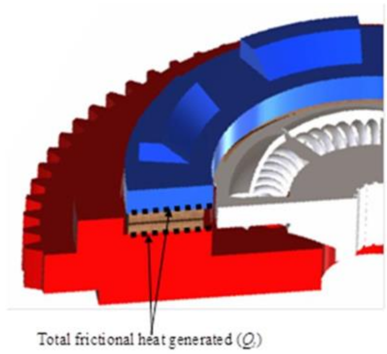

Figure 3. The thermal load on the contacting surface of clutch system

3. FINITE ELEMENT FORMULATION

This section presents the details to build the finite element model and the assumptions that are necessary to achieve the numerical analysis. The transient solution is involved time dependent function of the heat transfer.

The temperature will be changed in a unit volume of a specific material will be resisted by the thermal mass that depends on density (*ρ*) and specific heat (*c*). It can be expressed the finite element form of the transient problem as [25]

$$[C]\{\dot{T}\}+[K]\{T\}=\{F\} \quad (7)$$

Where,
[*C*]: Specific heat matrix
[*K*]: Conductivity matrix
{*T*}: Vector of nodal temperatures
{*Ṫ*}: Derivative of temperature with time $(\partial \dot{T}=\partial T/\partial t)$
{*F*}: Applied heat flows.

The mesh element that selected to build the finite element model is considered the effective key to obtain the accurate results of temperature distribution. It was used Crank-Nicolson method as an unconditionally stable scheme. In this research paper, Ansys/workbench was to study the transient conduction problem of the friction clutch system under the dry condition.

It was assumed the thermal load based on the theory of design (uniform wear) for the friction clutches. This means that the thermal load is uniform over the contacting surfaces at any instant of time during the sliding phase. All materials properties are used in this analysis are supposed to be homogeneous and isotropic. Also, the properties of materials are temperature-independent. Table 1 lists all material properties and operational parameters of the case study. The value of the heat transfer coefficient which used to achieve the numerical computation was 40.89 W/m^{2}K [2] and assumed to be a constant over all exposed surfaces. In the analysis, the intial temperture for the entire system is 300K.

Table 1. Operational parameters and material properties of the friction clutch system [4]

Parameters	Values
Inner radius, r_c and r_{cu} [m]	0.06
Outer radius, r_c and r_{cu} [m]	0.0792
Thickness of axial cushion, [m]	0.004
Inner radius, r_p [m]	0.06
Outer radius, r_p[m]	0.091
Thickness of pressure plate, [m]	0.01
Inner radius of flywheel, [m]	0.0485
Outer radius of flywheel, [m]	0.097
Thickness of flywheel, [m]	0.0194
Applied pressure, p_a [MPa]	1
μ	0.3
ω_o [rad/sec]	295
No. of friction surfaces, n	2
ρ_c [kg/m^3]	1000
ρ_{cu}, ρ_f, ρ_p [kg/m^3]	7200
c_c [J/kg K]	1400
c_{cu}, c_f, c_p [J/kg K]	450
K_c [W/mK]	0.75
K_{cu}, K_f, K_p [W/mK]	56
t_s [s]	0.4

Figure 4 illustrates a sector of the three-dimensional finite element model of the assembly of the flywheel, clutch disc and pressure plate. Owing to the symmetry of the geotry and load, it was used only a sector of the total model in order to reduce the computation time. The element (SOLID90) was selected to build the finite element model, where this element contains 20 nodes with a single degree of freedom which is temperature. This element has compatible with temperature shapes and it's very suitable to the model which has curved boundaries.

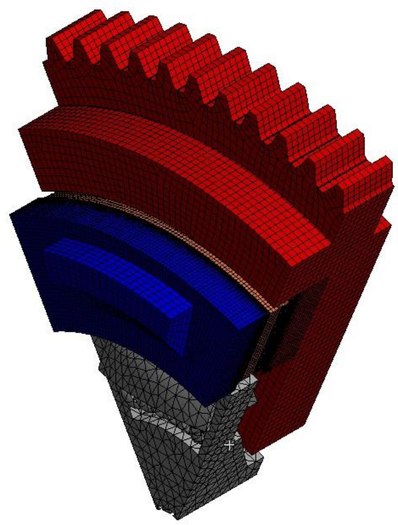

Figure 4. Finite element model of the clutch system (sector)

It was accomplished study of the mesh sensitivity in order to select the optimal mesh based computational accuracy point of view.

4. RESULTS AND DISCUSSIONS

I was achieved the finite element analysis based on the developed model of the dry friction clutch using Ansys/APDL to study the temperature field during the sliding time under the uniform wear assumption.

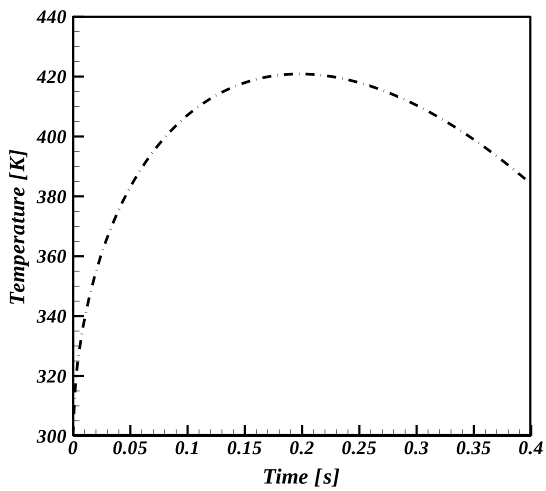

Figure 5. The maximum temperature of the friction clutch system during the sliding period

Figure 5 illustrates the highest temperature during the sliding period in the components of the friction clutch. It can be seen that the temperature increased from the initial condition (t_s=0) to the maximum value that occurred at approximately the mid time of heating phase (t_s=0.25s), later on the temperature decreased with time to end of the heating phase. The maximum difference in temperature ($T_{max.}$-T_i) occurred at the mid time of heating phase (t_s =0.2) which was (420.8 K).

The contours of the temperature field of the friction clutch disc, flywheel and pressure plate at different intervals of sliding time are shown in Figures 6. It can be noticed that the distribution of temperatures is approximately uniform on the contacting surfaces. These results were obtained based on the thermal load that calculated when assumed that the rate of wear is uniform (old friction clutch) over the contacting surfaces. In other words, the thermal load (the frictional heat) was generated uniformly at the interface between the contacting surfaces.

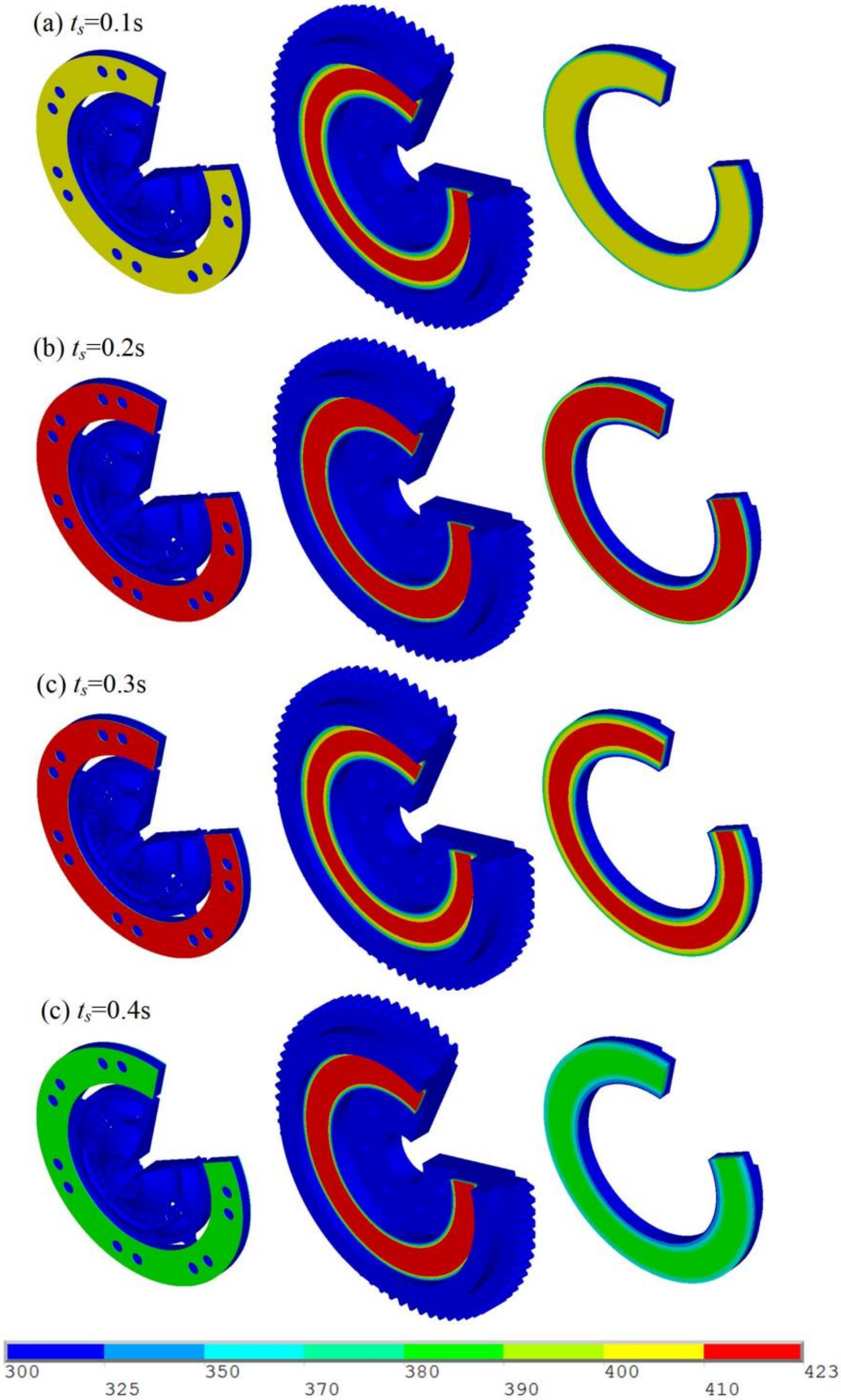

Figure 6. Distributions of temperature of the friction clutch system at different time of sliding period

5. CONCLUSIONS AND REMARKS

In this work, a significant numerical approach was introduced to solve accurately the thermal problem of the friction clutch system with one disc when both sides were effective. The analysis covered the sliding time within a single engagement. It was built 3dimensional finite element model to obtain the temperature distribution during the whole period of sliding.

The results proved the validity of the developed model, where the temperature was distributed uniformly over the surfaces of contact during the heating phase. The results showed that the maximum temperature occurred at approximately the mid time of the heating phase. In general, it has been observed that the highest temperature generated at the interface between the contacting elements. The thermal influences decreased when going toward the depth of clutch disc (friction material) to a minimum value approximately zero at midpoint of thickness.

Building this finite element model is considered very important forward step to explore the solution of more complex problems. Where, this paper is a preliminary investigation and will be followed by other future researches that will be investigated deeply the unsymmetrical load problem, effect of surface roughness, damaged contacting surfaces etc.

REFERENCES

[1] O.I. Abdullah, J. Schlattmann, A. Senatore, A. M. Al-Shabib: Investigation of thermoelastic problem of multiple-disc friction clutches applying different thermal loads, Heat and Mass Transfer, Vol. 54, No. 11, pp. 3461–3471, 2018.

[2] O.I. Abdullah, J. Schlattmann, M.H. Majeed, and L.A. Sabri: The Distribution of Frictional Heat Generated Between the Contacting Surfaces of the Friction Clutch System, International Journal on Interactive Design and Manufacturing, 2018.

[3] O.I. Abdullah, J. Schlattmann, M.H. Majeed, and L.A. Sabri: The Temperatures Distributions of a Single-Disc Clutches Using Heat Partitioning and Total Heat Generated Approaches, Case Studies in Thermal Engineering, Vol. 11, pp. 43-54, 2018.

[4] O.I. Abdullah, J. Schlattmann: Thermoelastic Analysis of Grooved Friction Clutches Using Finite Element Method, Tribology Transactions, Vol. 60, No. 6, pp. 1011-1021, 2017.

[5] O.I. Abdullah, J. Schlattmann: Thermal Behavior of Friction Clutch Disc Based on Uniform Pressure and Uniform Wear Assumptions, Friction, Vol. 4, No. 3, pp. 1-10, 2016.

[6] O.I. Abdullah, J. Schlattmann: Temperature Analysis of A Pin-On-Disc Tribology Test Using Experimental and Numerical Approaches, Friction, Vol. 4, No. 2, pp. 1-9, 2016.

[7] O.I. Abdullah, M.J. Akhtar, J. Schlattmann: Investigation of Thermo-Elastic Behavior of Multidisk Clutches, Journal of Tribology, Vol. 137, No. 1, pp. 1-9, 2015.

[8] O.I. Abdullah, J. Schlattmann: An Investigation into the Thermal Behavior of the Grooved Dry Friction Clutch, Journal of Tribology, Vol. 136, No. 3, pp. 1-6, 2014.

[9] O.I. Abdullah, J. Schlattmann: Computation of Surface Temperatures and Energy Dissipation in Dry Friction Clutches for Varying Torque with Time, International Journal of Automotive Technology, Vol. 15, No. 5, pp. 733-740, 2014.

[10] O.I. Abdullah, J. Schlattmann, A.M. Al-Shabibi: Thermo-Mechanical Analysis of the Dry Clutches Under Different Boundary Conditions, Journal of Tribology in Industry, Vol. 36, No. 2, pp. 172-180, 2014.

[11] O.I. Abdullah, J. Schlattmann, A. M. Al-Shabibi: Stresses and Deformations Analysis of a Dry Friction Clutch System, Tribology in Industry, Vol. 35, No. 2, pp. 155-162, 2013.

[12] O.I. Abdullah, J. Schlattmann: Finite Element Analysis of Temperature Field in Automotive Dry Friction Clutch, Tribology in Industry, Vol. 34, No. 4, pp. 206-216, 2012.

[13] K. Topczewska: Analytical model for investigation of the effect of friction power on the thermal stresses in friction elements of brakes, Journal of Theoretical and Applied Mechanics, Vol. 56, No. 4, pp. 1017-1027, 2018.

[14] K. Topczewska: Temperature distribution in a brake disc with variable contact pressure, Technical Issues, Vol. 2016, No. 1, pp. 90-95, 2016.

[15] K. Topczewska: Frictional heating with time-dependent specific power of friction, acta mechanica et automatica, Vol. 11, No. 2, pp. 111-115, 2017.

[16] K. Topczewska: The temperature of a brake disc during frictional heating with linear distribution of the contact pressure, Technical Issues, Vol. 2016, No. 3, pp. 113-119, 2016.

[17] K. Topczewska: Analytical model for investigation of the effect of friction power on the thermal stresses in friction elements of brakes, Journal of Theoretical and Applied Mechanics, Vol. 56, No. 4, pp. 1017-1027, 2018.

[18] K. Stevens, M. Tirovic: Heat dissipation from a stationary brake disc, Part 1: Analytical modelling and experimental investigations, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 232, No. 9, pp. 1707-1733, 2018.

[19] A. Yevtushenko, M. Kuciej, K. Topczewska: Analytical model for investigation of the effect of friction power on temperature in the disk brake, Advances in Mechanical Engineering, Vol. 9, No. 12, 2017.

[20] A.A. Yevtushenko, P. Grzes: Mutual influence of the sliding velocity and temperature in frictional heating of the thermally nonlinear disc brake, International Journal of Thermal Sciences, Vol. 102, pp. 254-262, 2016.

[21] A.M. Al-Shabibi: Solution of heat conduction problem in automotive clutch and brake systems, In *ASME 2008 Heat Transfer Summer Conference collocated with the Fluids Engineering, Energy Sustainability, and 3rd Energy Nanotechnology Conferences*, pp.321-326. American Society of Mechanical Engineers, 2008.

[22] A.M. Al-Shabibi, J.R. Barber: Transient solution of 2-D TEI problem using reduced order models, SAE transactions, pp. 1244-1248, 2001.

[23] A.M. Al-Shabibi: Solution of a Non-Linear Heat Conduction Problem, In *Automotive Clutch and Brake Systems. In ASME 2009 Heat Transfer Summer Conference collocated with the InterPACK09 and 3rd Energy Sustainability Conferences*, pp. 415-419 American Society of Mechanical Engineers, January 2009.

[24] A.M. Al-Shabibi: Solution for transient heat conduction problem with low Biot number, 9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, 2012.

[25] J. N. Reddy, D. K. Gartling: *The finite element method in heat transfer and fluid dynamics*, CRC press, 2010.