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The analysis of thermal losses in an induction motor

***Abstract**. Operation of any kind of machinery is always connected to efficiency and losses. The part of energy is always being dissipated to the surroundings. In the case of electric machines the losses result in heat generation. Present contribution introduces the numerical method for predicting and analysing the heat transfer including conduction, convection, and radiation at the specific operating regimes of electric motor. For numerical method validation, experimental system was used. The goal of analysis was to define the mathematical model for proper definition of heat transfer mechanisms.*

***Streszczenie.** Wszelkiego rodzaju działanie z urządzeniami związane są ze sprawnością i stratami. Część energii jest rozpraszana do otoczenia. W przypadku maszyn elektrycznych wynikiem strat mocy jest generacja ciepła. Artykuł przedstawia metodę numeryczną dla predykcji i analizy przepływu ciepła, włączając przewodnictwo, konwekcję i promieniowanie w specyficznym obszarach pracy silnika elektrycznego. Dla walidacji wyników użyto systemu eksperymentalnego. Celem analizy było zdefiniowanie modelu matematycznego dla właściwego opisu mechanizmu przepływu ciepła. (**Analiza strat cieplnych w silniku indukcyjnym**)*

Keywords: numerical simulation, heat transfer, thermal losses, induction motor.
Słowa kluczowe: symulacja numeryczna, przepływ ciepła, straty cieplne, silnik indukcyjny.

Introduction

Over the last decade, computer simulation has been increasingly used for various fluid dynamics examples at the field of machinery optimisation and development because of its undeniable advantages such as cost and efficiency comparing to experimental development. Hence, several studies of fluid flow and heat transfer in induction motors have been presented. Most of the studies are focused on the optimization of the induction motor characteristics to correlate the power with its thermal performance characteristics. Although experimental studies of thermal losses have been undertaken before, the method has still been constrained by two key facts, firstly the ability for discrete temperature point measurements and secondly the limitations of space in the body of motor.

According to this, present study introduces promising method for detailed analysis of thermal losses in the conventional induction motor made by commercial computational fluid dynamics software, based on the Reynolds Averaged Navier Stokes equations.

Theory of heat transfer

Fundamental methods of heat transfer include conduction, convection, and radiation. Although separate physical laws have been discovered to describe the behaviour of each of these methods, real systems may exhibit a complicated combination.

Conduction is an energy transfer across a system boundary due to a temperature difference by the mechanism of inter-molecular interactions. The flow of heat by conduction occurs via collisions between atoms and molecules in the substance and the subsequent transfer of kinetic energy. Conduction rate equation is described by the Fourier Law:

$$Q = \lambda A \nabla T \tag{1}$$

where Q presents heat flow; λ thermal conductivity, a thermodynamic property of the material; A surface area and ∇T temperature gradient.

Convection is an energy transfer across a system boundary due to a temperature difference by the combined mechanisms of intermolecular interactions and bulk transport. It is defined by:

$$Q = \alpha A_s \Delta T \tag{2}$$

where α present heat transfer coefficient which is not a thermodynamic property of the material; A_s present surface area from which convection is occurring and ΔT defines the temperature difference.

There exist two mechanisms of convection:

- Free or natural convection occurs when the fluid motion is caused by buoyancy forces that result from the density variations due to variations of temperature in the fluid.
- Forced convection is when the fluid is forced to flow over the surface by external sources such as fans, creating an artificially induced convection current.

Convection is usually the dominant form of heat transfer in liquids and gases.

Radiation heat transfer involves the transfer of heat by electromagnetic radiation that arises due to the temperature of the body. All objects with a temperature above absolute zero radiate energy and no medium is necessary for radiation to occur. It takes place even in and through a perfect vacuum. The rate of the radiation heat exchange between a small surface and a large surrounding is given by the following expression, derived from the Stefan Boltzman law:

$$Q = \varepsilon \sigma A \left(T_s^4 - T_{sur}^4 \right) \tag{3}$$

Where ε presents surface emissivity; σ presents Steffan Boltzman constant; A presents surface area; T_s present the temperature of surface; and T_{sur} present the temperature of surroundings.

Various mathematical methods have been developed to solve or approximate the results of heat transfer in different engineering systems. For the purpose of numerical simulation, heat transfer is defined with application of additional conservation equation to the governing equations.

The governing equations

All of the CFD, in one form or another, is based on the fundamental governing equations of fluid dynamics – the continuity, momentum and energy equations. These equations speak physics. They are mathematical statements of three fundamental physical principles upon which all of fluid dynamics is based:

- mass is conserved,
- Newton's second law,
- energy is conserved.

There exist integral and differential forms of the governing equations. The integral form of the equations allows the presence of discontinuities inside the fixed control volume and differential form of the governing equations assumes the flow properties are differentiable, hence continuous. This is particularly evident when we use the divergence theorem to derive the differential form from integral form – the divergence theorem assumes the mathematical continuity. This is the strong argument for the integral form of the equations to be considered more fundamental.

According to the fact of analysing the continuous flow properties, the differential form of governing equations will be presented.

The continuity equation is the resulting equation of the principle that mass is conserved. In differential form it can be written as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial u_j \rho}{\partial x_j}=0 \tag{4}$$

where u_j present velocity vector and ρ density.

The physical principle that mass is conserved can be also expressed as follows: The net mass flow out of the fluid element (fixed in space) must equal the time rate of decrease of mass inside the element.

The momentum equation is the resulting equation of Newton's second law. It says that net force on the fluid element equals its mass times the acceleration of the element. In general, there exist different sources of the force on the fluid element:

- Body forces act directly on the volumetric mass of the fluid element (gravitational, electric and magnetic forces) and
- Surface forces which act directly on the surface of the fluid element (pressure, shear and normal stresses).

In differential form the momentum equation can be written as:

$$\rho\frac{\partial u_i}{\partial t}+u_j\frac{\partial}{\partial x_j}e=\lambda\frac{\partial^2}{\partial x_j^2}T+S_e \tag{5}$$

The energy equation is resulting equation of the energy conserving law. The physical principle stated above is nothing more than the first law of thermodynamics which states that rate of change of energy inside fluid element equals net flux[1] of heat into element plus rate of work done on element due to body and surface forces.

In differential form the energy equation can be written as:

$$\frac{\partial e}{\partial t}+u_j\frac{\partial}{\partial x_j}e=\lambda\frac{\partial^2}{\partial x_j^2}T+S_e \tag{6}$$

where e presents thermal energy and S_e thermal energy sources.

The experimental setup

In this study, the thermal conditions of a 4-pole three-phase high-performance induction motor were analysed experimentally also. The experimental setup for measurement of rotating electrical machines operating characteristics is shown in Figure 1.

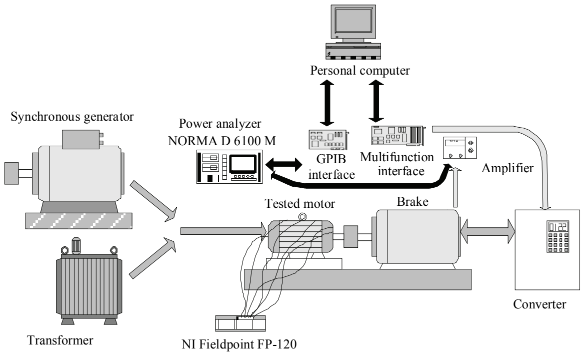

Fig.1. Experimental setup sketch

The main parts of setup are synchronous generator driven by a converter-fed induction motor (used for supplying tested motor), measurement equipment for motor characteristics measurements (power analyzer, amplifiers, multifunction cards, torque sensor, rotational speed sensor). For motor housing and stator winding temperatures measurement, an instrument for temperature measurements with thermocouples was used.

Fig.2. Tested motor

The position of each thermocouple on the motor's housing is presented in Figure 6. For adequate measurement results and their analysis the personal computer with LabVIEW software package was used.

The motor was rated for 2 kW at 1460 rpm (Table 1). The motor's power balance and the respective losses under different mechanical load conditions represented the input data for the thermal analysis.

Table 1. Nominal operating point

Nominal voltage	400 V
Nominal current	5,2 A
Nominal power	2 kW
Nominal speed	1460 rpm
Nominal frequency	50 Hz

The physical model and boundary conditions

The complete induction motor geometry was reduced to the domain shown at Figure 3.

The domain was composed of fluid part, where heat was convected to the surrounding air; aluminium ribs and stator made of steel where heat was conducted. With particular boundary prescription at the outer boundaries, the infinite air surrounding was prescribed. At the inner side of stator ribs, the insulation domain was placed and thermal losses –

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[1] The heat transfer in a given direction, when expressed in dimensions of energy per unit time per unit area perpendicular to the direction, is called the heat flux in that direction.

heat flux boundary condition was prescribed. Since the induction motor analysis present the case where all aspects of flow are symmetric about flat plane, symmetry boundary plane condition was applied as shown at figure 3.

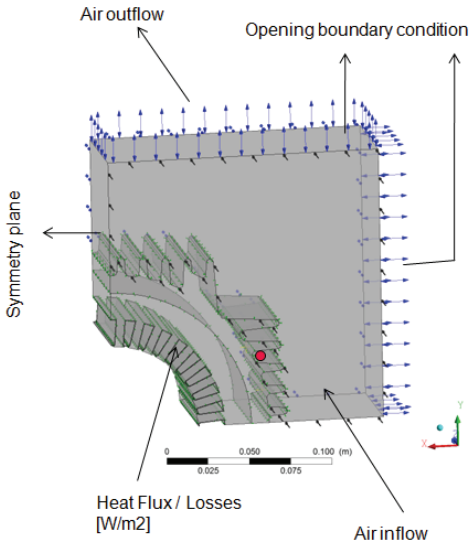

Fig.3. Boundary conditions.

The computational domain discretisation

The unstructured grid with tetragonal elements was applied for computational domain discretisation. The total number of 1.700.000 mesh elements was used. The iteration target residual criteria was set to the value $r = 10^{-6}$. Owing to the intensive heat transfer at the fluid-solid interface caused by the convection process, under relaxation[2] for the momentum equation was applied at the solver initialisation process. The heat and momentum transfer were controlled only by the prescribed time-step after transient initialisation phase.

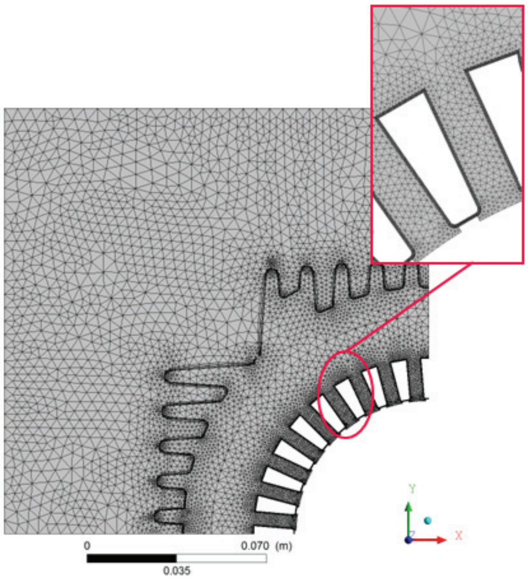

Fig.4. Domain discretisation

The simulation process was stable and conservative. The solution was inside the physical laws globally and locally which is evident from convergence plot shown in figure 5.

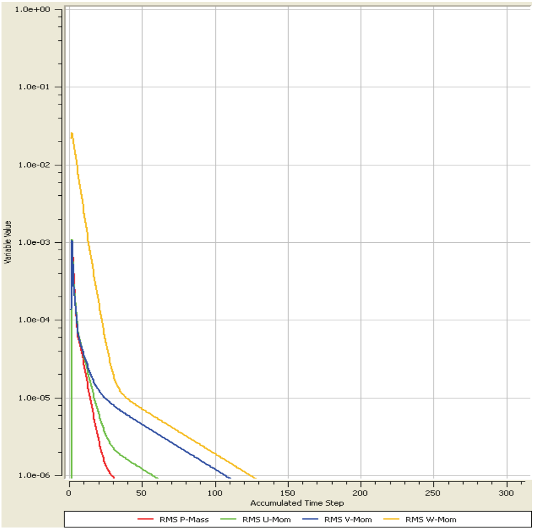

Fig.5. Convergence plot

The results

The numerical simulation was focused to the temperature field at the steady state condition. In order to follow the transient initialisation phase, control point was defined at the places where thermocouples were connected to the motor casing (Figure 6).

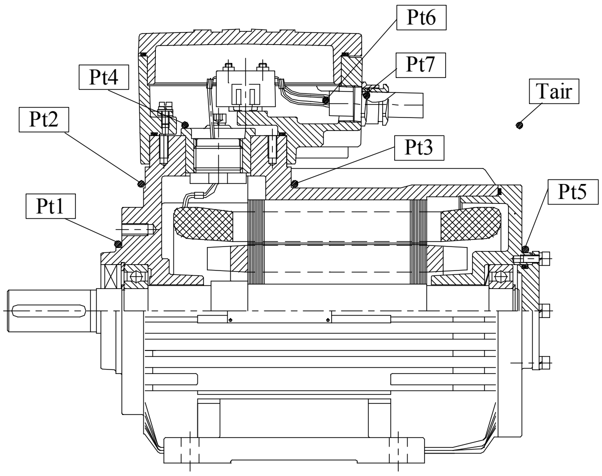

Fig.6. Thermocouples at the motor casing

Figure 7 shows that temperature stabilised at the value of T_{num} = 101°C, which was close to the experimental value of Texp = 102.8°C. According to this, excellent results agreement can be concluded for the analysed operating regime.

Thermal field visualisation plot is shown at the Figure 8. Figure 8 logical and visual confirms the method of solver under-relaxation during initialisation procedure. Presented temperature field confirms the boundary conditions definition and the fluid domain size.

There exists strong temperature gradient near the stator ribs which is connected to the relatively strong movement of hot air upwards. In order to achieve better operating conditions of the motor, the temperature field around ribs should be uniformed. In order to satisfy this requirement the geometry optimisation process should be applied at the

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[2] Under relaxation limit the influence of the previous iteration over the present one.

complete 360° cross-section of the motor for the case of natural convection.

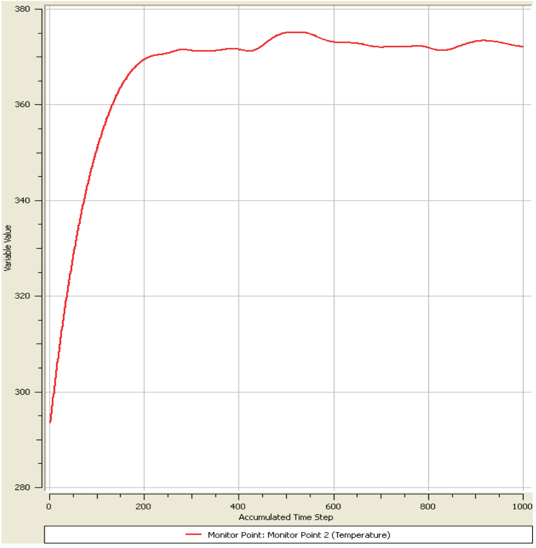

Fig.7. The temperature plot at the control point

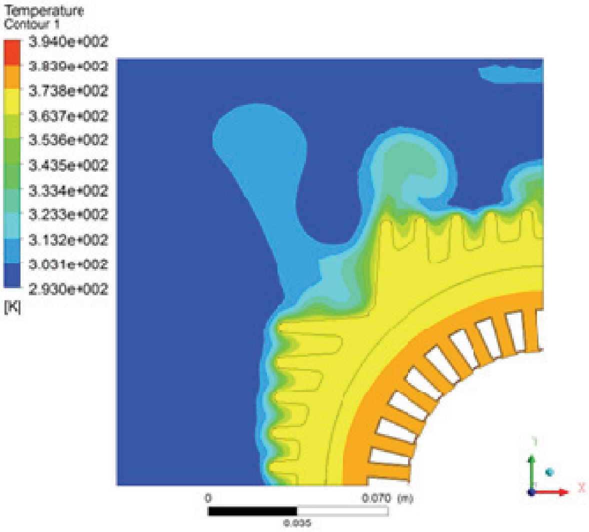

Fig.8. The temperature plot at the control point

In the case of forced convection, the fan connected to the motor axes assures the convection intensity and causes the homogenous temperature field with more acceptable operating regime.

In order to completely validate the result, additional measurements should be done with Thermal Imaging System.

The conclusion

CFD is useful tool for numerical simulations of conjugated heat transfer / thermal losses in an induction motor.

Complex physical pattern of analysed phenomena requires advanced experience at the field of numerical simulations and solver settings.

The numerical results follow the experimental values very good $\Delta T = 1,7\%$.

The construction details of motor must be included in the physical (CFD) model.

The major problem is in different dimension range of insulation thickness and gap size comparing to domain size, mesh sizing and computer memory limitations respectively.

Additional experimental work should be applied in order to completely confirm the presented method.

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