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A Design Methodology and Tool to Support Ecodesign Implementation in Induction Hobs

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Abstract**—**Nowadays, the European Ecodesign Directive has emerged as a new approach to integrate environmental concerns into the product design and related processes. Ecodesign aims to minimize environmental impacts throughout the product life cycle, without compromising performances and costs. In addition, the recent Ecodesign Directives require products which are increasingly eco-friendly and eco-efficient, preserving high-performances. It is very important for producers measuring performances, for electric cooking ranges, hobs, ovens, and grills for household use, and a low power consumption of appliances represents a powerful selling point, also in terms of ecodesign requirements. The Ecodesign Directive provides a clear framework about the sustainable design of products and it has been extended in 2009 to all energy-related products, or products with an impact on energy consumption during the use. The European Regulation establishes measures of ecodesign of ovens, hobs, and kitchen hoods, and domestic use and energy efficiency of a product has a significant environmental aspect in the use phase which is the most impactful in the life cycle. It is important that the product parameters and performances are not affected by ecodesign requirements from a user's point of view, and the benefits of reducing energy consumption in the use phase should offset the possible environmental impact in the production stage. Accurate measurements of cooking appliance performance are essential to help the industry to produce more energy efficient appliances. The development of ecodriven products requires ecoinnovation and ecodesign tools to support the sustainability improvement. The ecodesign tools should be practical and focused on specific ecoobjectives in order to be largely diffused. The main scope of this paper is the development, implementation, and testing of an innovative tool, which could be an improvement for the sustainable design of induction hobs. In particular, a prototypical software tool is developed in order to simulate the energy performances of the induction hobs. The tool is focused on a multiphysics model which is able to simulate the energy performances and the efficiency of induction hobs starting from the design data. The multiphysics model is composed by an electromagnetic simulation and a thermal simulation. The electromagnetic simulation is able to calculate the eddy current induced in the pot, which leads to the Joule heating of material. The thermal simulation is able to measure the energy consumption during the operational phase. The Joule heating caused from the eddy currents is the output of electromagnetic simulation and the input of thermal ones. The aims of the paper are the development of integrated tools and methodologies of virtual prototyping in the context of the ecodesign. This tool could be a revolutionary instrument in the field of industrial engineering and it gives consideration to the environmental aspects of product design and focus on the ecodesign of energy-related products, in order to achieve a reduced environmental impact.

Keywords**—**Ecodesign, induction hobs, virtual prototyping, energy efficiency.

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I. Introduction

EUROPEAN Directive 2009/125/EC [1] establishes the ecodesign requirements related to domestic and commercial kitchen appliances typically used in households establishments such as cookers, hobs, grills, and electrical mains. The European Regulation (EU) No 66/2014 [2] and in particular the European standard EN 60350-2 [3] "Household electric cooking appliances - Part 2: Hobs - Methods for measuring performance" regulate the measurement of energy consumption of induction hobs.

In the environmental impact assessment of a product, energy aspects play a role in the choice between different product alternatives, the subsequent behavior of the consumer in use phase of a product, and consequently in the decision of how to dispose of the product at the end of use phase. The use phase is most contributing on the life cycle stage for some products, especially for the households' appliances, so a robust modelling of this stage is fundamental [4].

During the last years, the manufacturing industries have been completely rethinking their way of designing and manufacturing by implementing responsible strategies which are focused on products that have an ecological, social, and economic value. Ecodesign is an approach that puts evidence on the environmental aspects of a product, during the design and development stages, with the goal of minimizing the environmental impact [5]. The important aspect of the ecodesign is the combination of the process engineering product design procedures with the consideration of environmental aspects. The development of a product has to satisfy criteria such as price, performance, quality, and in a ecodesign approach, these aspects can be also focused on the environmental requirements [6], [7]. Energy efficiency has a significant environmental aspect, and the employment of more efficient energy consuming products could lead to a reduction in the total amount of the global energy consumed. This context requires the employment of design tools and methodologies able to support the designer in the early estimation of product performances using virtual prototyping tools. The product engineering needs innovative, functional, and rapid design methodologies to have a more energy-aware product design in accordance with the recent legislation.

The main scope of this research is the development of integrated tools and methodologies of virtual prototyping. The work is based on a multiphysics analysis in order to have a virtual prototype which is validated with experimental tests [8]. In this context, the induction hobs are a category of products involved in the Ecodesign Directives from the design product. Domestic induction heating cookers are becoming one of the leading cooking systems due to their advantages, e.g. energy efficiency, rapid heating, cleanliness, and user safety. These benefits are achieved thanks to the fact that the heat is generated in the base of the pot. Induction hob consists basically of a power electronics circuit, a coil (inductor), and a ceramic glass. Power electronics fed the copper coil with high frequency current that produces an oscillating magnetic field. This magnetic field induced current in the bottom of the cookware. The induced currents are generated according to the Faraday's law by the frequency current flowing through the bottom of the ferromagnetic cookware and heat it. The ferromagnetic pot is placed on the ceramic glass instead of the surface of the hob [9], [10]. At the same time, these currents are supplied by the power electronics depending on the power level selected by the user by means of the user interface.

During the last years, many researchers have focused on the induction heating with studies on the development of high efficiency power electronic systems, on the design of the inductor and on the efficiency improvement of the cooking processes by means of the pot optimization. To improve the performances of induction cookers, a great number of research works have been carried out, and most of these works are focused on the increase of energy efficiency, reduction of manufacturing, and use costs [11], [12]. Some authors have studied the behavior of cooking stoves and pots with theoretical models and experimentation, and in particular case, the thermal efficiency of pots was calculated and measured [13]. Other researchers have focused on the efficiency improvement of the cooking processes by means of the pot optimization. In the other papers, a study of the efficiency of pots through experimental and neural network method is presented. Other works have focused on models that consider a uniform distribution in the bottom of the pot [14], [15]. These works needed physical prototypes, and their study is not focused on a product based on Ecodesign Directive since its early design. Against this background, it is important to employ design tools and methods able to support the designer in the early estimation of the product energy performances using virtual prototyping tools. Other works have focused on this important aspect, with the development of a prototypical software tool in order to simulate the energy performances of a kitchen hood configurations or with the study of a model which is able to estimate the energy efficiency of the induction hobs during the operational phase [16], [17].

From an ecoproduct point of view, it is important to have a systematic approach in the design in order to have a knowledge about different flows of energy and product performances.

This paper investigates the structure and associated problems of heating performance for conventional induction cooker and studies the heating distribution of induction cooker as the result of magnetic field distribution.

This paper is organized as follow: in Section II, the methodology is presented; in Section III, the product and mechanism of heat transfer are presented for better understanding the of the process of modeling. The model development and the experimental validation through the comparing of the real test data with the simulations are carried out in Section IV. Finally, Sections V and VI show the discussion and the conclusions of the proposed study.

II. Methodology

The aim of this work is to develop a methodology which is able to support the design during the whole life cycle of the product. The idea is to develop a flexible method based on virtual prototyping tools that can simulate the performance of induction hobs, and in particular ecodesign regulations required by European commission. Fig. 1 shows the proposed methodology. The heart of the approach is based on a multiphysics system which is able to solve two different models: the electromagnetic model and the thermal model.

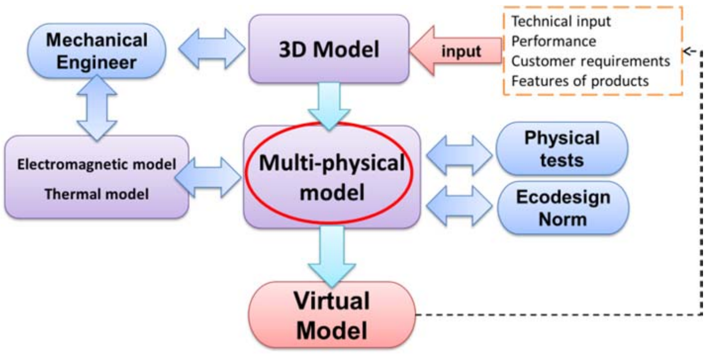

Fig. 1 Methodological approach

The described methodological approach is implemented in order to lead the modeling of a virtual prototype which reproduces the behavior of an induction hob, based on the induction heating. In particular, the induction heating is a physical process for heating a magnetic material by an electromagnetic field which causes eddy currents in the mean producing thermal losses.

The methodology is composed by different phases and considers the technical input of the induction hobs, the performance, the customer requirements, the necessity to obtain good performances and the features of the product. The first phase of the approach is the definition of a 3D model, wherein according to the inputs, a functional model is created to analyze. The 3D model is the starting point of the methodology. The multiphysics models allow to simulate the electromagnetic and thermos fluid dynamics behavior using a FEM and CFD tools. The electromagnetic model solves the equations of Maxwell (FEM tools), while the thermal model solves the thermodynamics classical equations (CFD tools).

Depending on the current and frequency that passes in the copper coil, it is possible to evaluate the eddy currents generated on the bottom of the pot and the relative heat generated by the Joule effect. The heat which is obtained through the electromagnetic model is an input to the thermal module, and is able to simulate the fluid-dynamic behavior of the product.

The realized numerical models are defined test conditions. It is possible to simulate all operating conditions, and evaluate the performance in any situation. In particular, the method is used to know from the early stages of product the system performance described in the ecodesign regulations. The physical test modules and ecodesign norm contain information regarding experimental tests of the product and test methodologies for the certification of the systems.

The experimental tests are useful to validate the numerical model. The results comparison between the numerical simulations and physical tests are used to assess the correctness of the numerical model and if necessary to correct the numerical simulation. The ecodesign norm module contains the list and the methods for testing procedure in order to identify the main inputs and outputs of the simulation.

The last step of multiphysics simulation is the results comparison. It is the responsibility of the designer to analyze the model obtained by evaluating product performance compared to the design values. The methodology has been applied to the simulation induction cooktops, but considering the flexibility of the method can also be applied to different types of product.

III. Induction Hob

An induction hob consists of inductor, some ferrite bars below the coil screened by aluminum and the load (pot) above the coil. Inductor of the induction system is a spiral planar coil which is fed by a medium frequency power source [18].

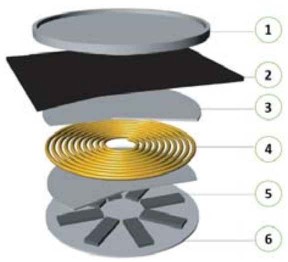

Fig. 2 Induction system structure: (1) load, (2) glass-ceramic material, (3) electric insulation material, (4) inductor, (5) flux conveyor (ferrite bars) and (6) aluminum shield

According to Faraday's law, the alternating magnetic field induces eddy currents in the metal pot, and additionally, ferromagnetic material produces magnetic hysteresis, both phenomena heat up the pan. Ferrite is located under the coil as a mica shielding to protect the electronic control system which is usually placed under applicator. The planar coil generates a current density inside the bottom of the cooking vessel. This current is dissipated because of the Joule effect and generates a power density distribution which heats the material (1):

$$P = \frac{J^2}{\sigma e_p} \tag{1}$$

where P is the power density distribution, J is the current density, σ is the electrical conductivity of the material and e_p is the thickness of the bottom of the disk [19].

The pot is placed over a ceramic glass which electrically isolates the inductor from the user. The heat generated in the bottom is transferred by conduction to the glass through a thermal contact conductance, which includes the imperfect contact between both surfaces due to the intrinsic rugosity of the materials. There are losses to the environment on the top surface of the bottom, the disk border, and the glass due to the convection and radiation.

The temperature reached inside the bottom of a pot during the heating is the consequence of the heating source and the power transmission. The temperature trend on each point of the base of a cooking vessel, placed over a heating source, obeys the heat equation (2):

$$P + \lambda \nabla^2 T = \rho C_p \frac{\partial T}{\partial t} \tag{2}$$

where P is the volumetric power density generated by the heating source. The second term is the heat flux of conduction, where $\nabla^2 T$ is the Laplacian of temperature T, and λ is the heat conductivity of the material. The term in the second member is the variation of the energy stored in the system with time, where the material has density ρ and specific heat capacity C_p. In this study, the pot is modelled as a thin disk of homogeneous ferromagnetic material with thermal properties and geometry known.

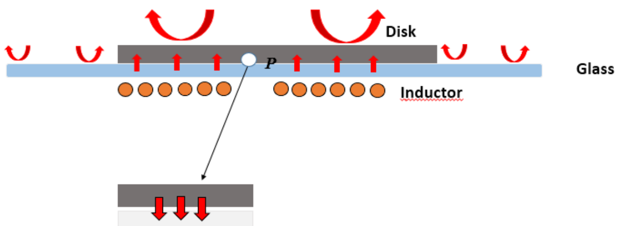

Fig. 3 Simplification of the electromagnetic and thermal phenomenon

The model shown in Fig. 3 represents the main flux of the system: the power generated in bottom of the pot, the heat transferred from the bottom of the pot by conduction to the glass, the losses to the environment from the bottom of the pot and the glass.

The ways that heat can be transferred into the system at different temperature are three mode: radiation, convection, and conduction. To get the equations, some books on heat and mass transference have been used [20], [21]. The parameters are in International System units. The amount of energy transferred due to radiation, convection, and convection can be expressed as (3)-(5):

$$Q_{radiation} = \xi \cdot A \cdot ({T_1}^4 - {T_2}^4) \quad (3)$$

$$Q_{convection} = h \cdot A \cdot (T_1 - T_2) \quad (4)$$

$$Q_{conduction} = k \cdot A \cdot (T_1 - T_2)/L \quad (5)$$

where ξ is the emissivity of the body, A is the area which exchanges heat, σ is the Stefan-Boltzmann constant, T_1 and T_2 are the temperatures of heat exchange, h is the convection coefficient, L is the length between T_1 and T_2 and k is the thermal conductivity. The convection coefficient has to be calculated from the dimensionless Nusselt number which is the ratio of convective to conductive heat transfer. The Nusselt dimensionless number has to be calculated through different empirical expressions for each different situation in which other dimensionless numbers as Rayleigh or Prandtl are involved.

IV. Virtual and Experimental Tests

The aim of this work is to create a virtual model to simulate the performances of an induction hobs. In order to validate the virtual model, the experimental tests of the system are presented and compared. Both the simulation and experimental results indicate that the study is a valid support to study the heating performances and to support the design of induction cooker.

This investigation can be considered as a support to the research work and to a methodology of calculation concerning the approaches that are available from a theoretical point of view in heat transfer.

The study is based on the analysis of temperature reached by the disk at different level of power and it investigates from where and how the energy/heat comes into the system, how it passes through the medium.

A. Virtual Tests

In this study, the system has been simplified and a ferromagnetic disk is used instead the traditional plot.

The structure of the system is represented in Fig. 4. The principal components are: a pan bottom plate that represents the load of the system and which is modelled as a steel ferromagnetic disk (diameter 180 mm, thickness 5 mm), a cooking surface in conventional ceramic glass, an inductor (diameter 180 mm), a layer of electric insulation material (a sheet of mica), a flux conveyor consisting of eight ferrite bars.

The aim of the virtual tests is to create a virtual model to simulate the performances and the behavior of the induction hob. The application of the approach, for the analysis of the induction heating system, requires a multi-physics approach for solving the electromagnetic and fluid dynamic problem. The induction heating problem is solved by an iterative solution of the time harmonic electromagnetic and the transient thermal problem. A FEM analysis allows to study the electromagnetic behavior of the System in Figs. 5 and 6. The FEM uses a self-adaptive meshing techniques to obtain a good compromise between the computational cost, due to the number of elements necessary to discretize the structure, and accuracy of the proposed solution.

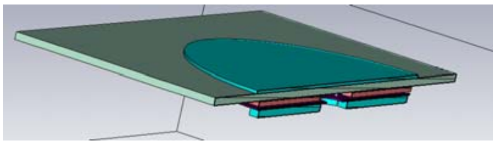

Fig. 4 Section of the complete system

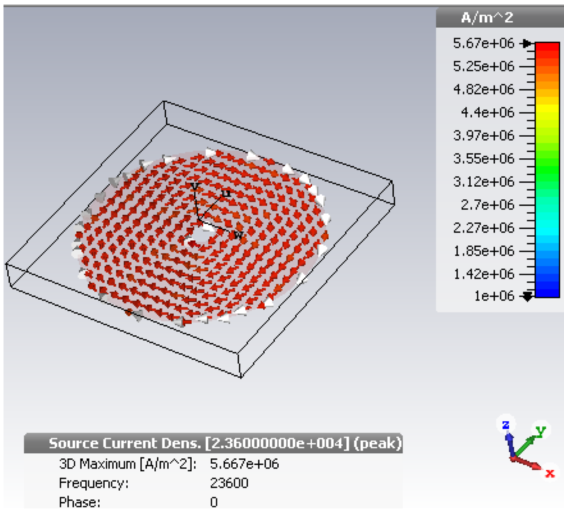

Fig. 5 Distribution of the current density in the disk

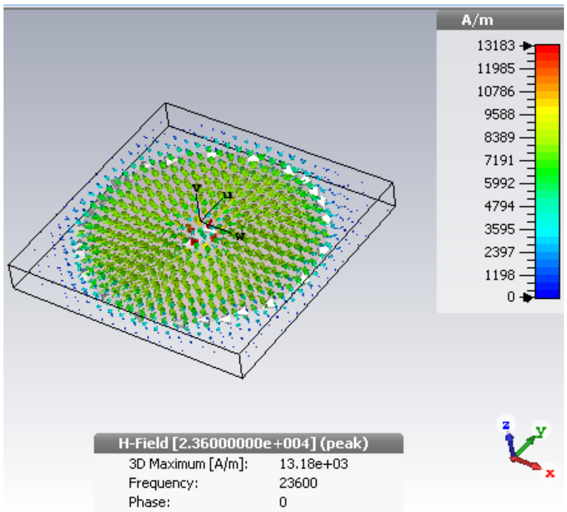

Fig. 6 Distribution of the magnetic field

A CFD analysis is used to investigate the thermal fluid dynamic behavior of the system analyzed. The output of the electromagnetic analysis is the value of power produced on the bottom of the pot, while the thermal fluid dynamic simulations investigate the heat exchange and distribution of temperature on the disk.

The research work focused the attention on the thermal model and the investigation of the heating distribution inside the disk. The virtual model is characterized by several thermophysics parameters, including thermal conductivity, specific heat capacity, and thermal diffusivity. The principal boundary conditions considered are the total pressure (pt = 101,325 Pa) and the ambient temperature (T=298 K). No-slip conditions were applied to all the domain walls. The simulations were considered to solve the transient and incompressible flow, where the air has been considered as a perfect gas. The simulations are performed at different power level to better investigate the thermal behavior of the disk. The input of the thermal simulations is the active power measured by the electromagnetic simulation. In Figs. 7 and 8, the sequence of heating of the disk is presented at the power of 700 W.

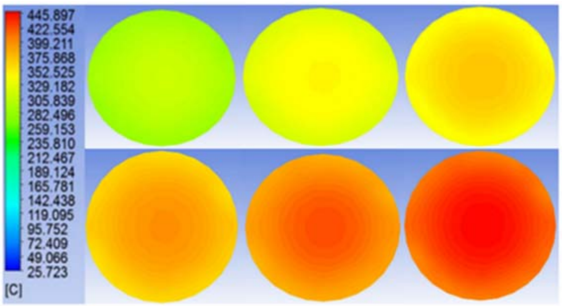

Fig. 7 Temperature of the disk

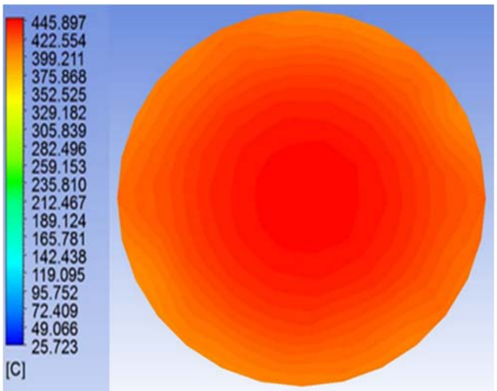

Fig. 8 Temperature of the disk after 300 s

As shown, there is a homogeneous temperature distribution, with the highest values of temperature in the central area of the disk. In addition, in order to evaluate the interaction of the thermal system with the external environment, a section of the model is shown in Figs. 9 and 10. In the figures, it is possible to observe the hottest part in the central area of the disk and the simulation of thermal convection of the air surrounding the disk. Regions with red hues designate hot areas, while regions with blue hues are cold. The hot layer sends plumes of hot air upwards, and likewise, cold air from the top moves downward.

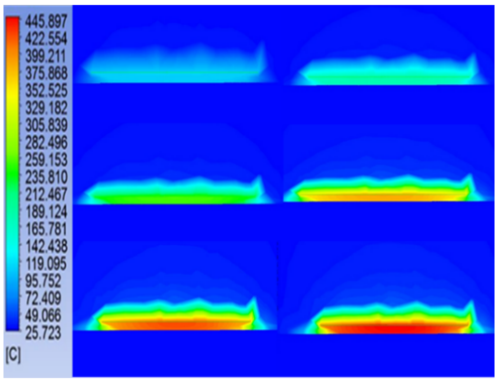

Fig. 9 Temperature on the cross section of the model

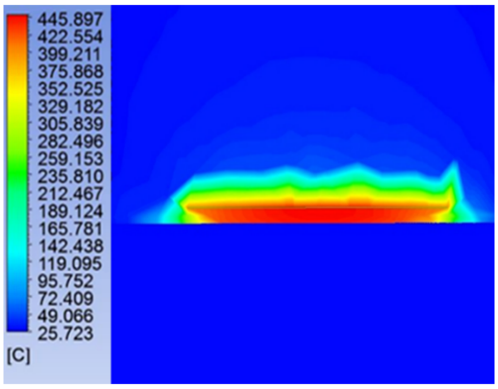

Fig. 10 Temperature on the cross section after 300 s

B. Experimental Tests

In order to validate the virtual tests have been conducted physical tests. The hob used for experimental tests shall be the same one used in simulations. Fig. 11 and Table I show the technical specifications of the hob used.

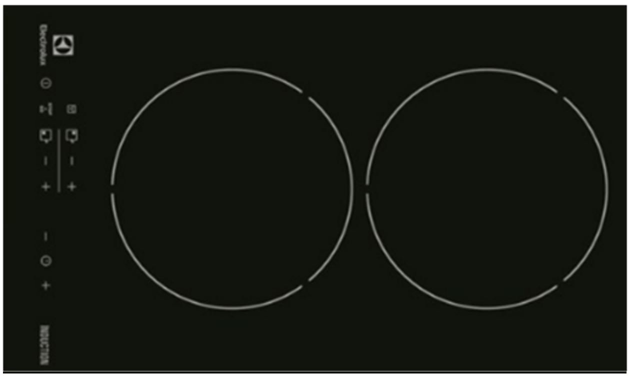

Fig. 11 Induction hob used in the experimental tests

As shown in Table I, the real hob has a different level of power the maximum power consumption is 3600 W. Fig. 12 shows the cooking zone under test which is the area marked in yellow color. The test is carried out at the laboratory of Università Politecnica delle Marche in Ancona. The tests presented try to show the robustness of the model. They are carried out at a cooking zone of 180 mm of diameter with different power levels to check the performances of the virtual model presented in this paper.

TABLE I
TECHNICAL SPECIFICATION

Ceramic induction: modular system – square-30cm;
2 cooking zone;
Electronic control: touch control;
Functional additional power;
Digital display;
Timer;
Programmer fine cooking;
Residual heat indicator light;
Maximum power consumption: 3.6 kW
System for easy installation

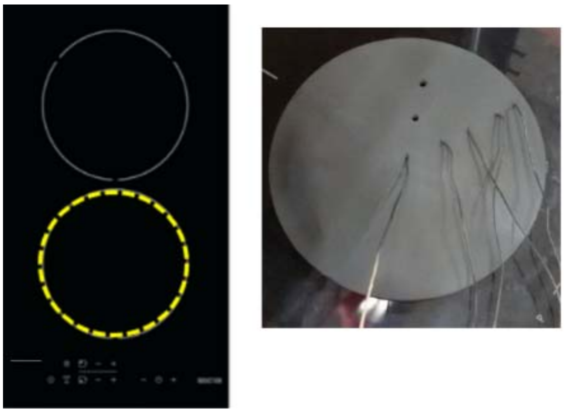

Fig. 12 Cooking zone and disk under test

In the test bench, the disk is positioned on the hob in correspondence of the cooking zone. The thermocouples employed in this test are type K. The type K thermocouples (chromel-alumel) usually work in most applications as they are nickel based and exhibit good corrosion resistance and it is characterized by a sensitivity approximately of 41 µV/°C. Due to its reliability and accuracy, the type K thermocouple is used extensively at temperatures up to 1260 °C.

The measuring points of thermocouples must record the temperature on top surface of the disk (so, the metal's temperature). The thermocouples are positioned in different points in order to investigate the global heating of the disk, considering a radial distance from the center (1* in the center, 2* at 25 mm, 3*at 45 mm, 4* at 65 mm, 5* at 80 mm) as shown in Fig. 13. In addition, the disk is painted using a special film in order to set the value of emissivity (ε = 0,95) in order to have a good thermal camera acquisition. A data taker acquires the thermocouples signals and plots the temperatures.

The level of electric power is investigated using a wattmeter connected to the hob. The wattmeter is connected, through its terminal, to the phase conductor of the cable.

An infrared thermal camera is positioned above the disk to investigate the thermal map of temperature on the disk as presented in Figs. 14 and 15. It is important to specify that the sequence of thermal camera images shows the heating up to 250 °C because of the full scale reached by the instrument.

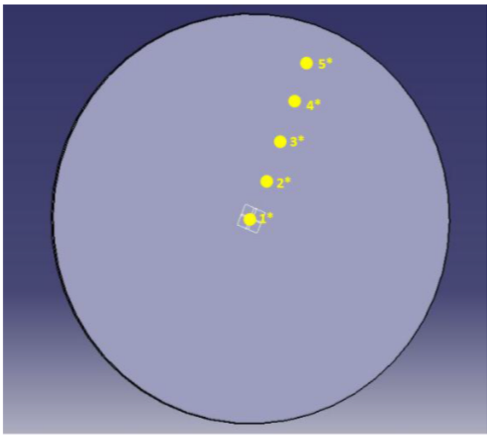

Fig. 13 Position of thermocouples positioned on the disk

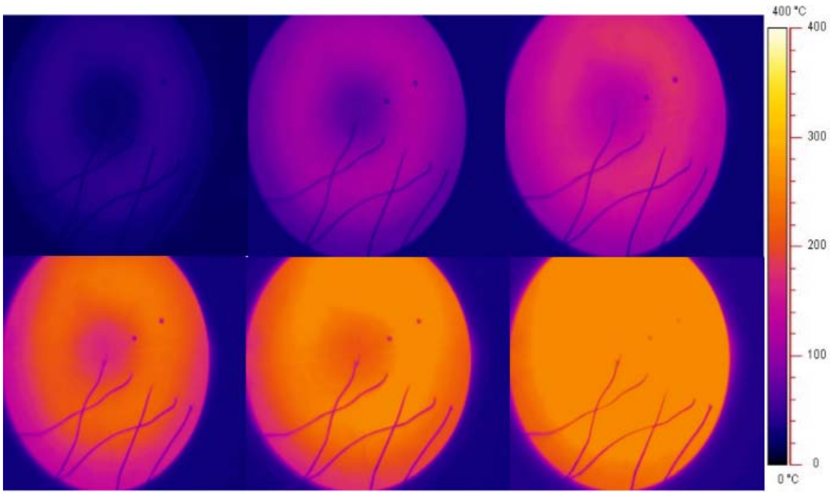

Fig. 14 Thermal map of temperature on the disk reached by infrared thermal camera

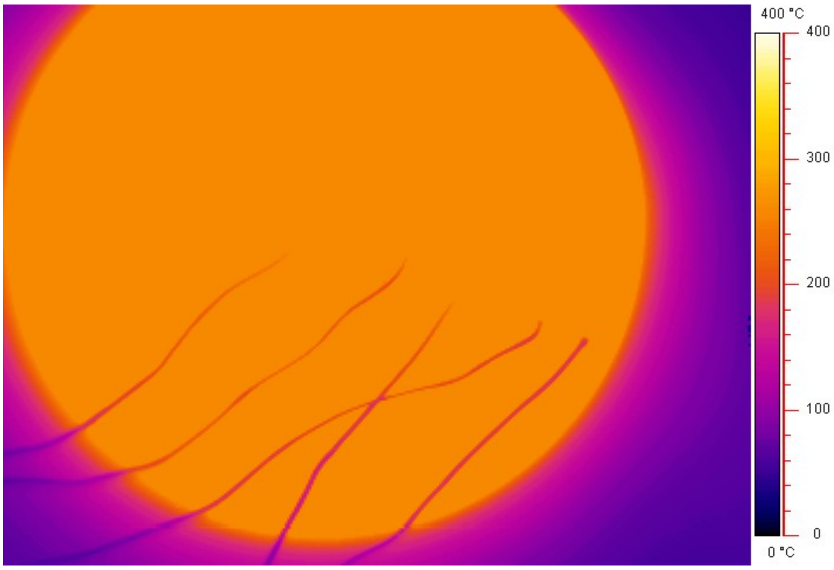

Fig. 15 Particular of infrared thermal image

After each test, necessary several minutes have been time to achieve the ambient temperature for the disk, the internal and electronic components of the hob in order to have the best operative conditions. Each test has been carried out at the same operating conditions: starting temperature of disk and of the glass of the hob is the ambient temperature.

The temperature investigation is performed on power different level to have a good temperature map of the temperature reached by the disk to validate the virtual tests.

V. Comparison and Discussion of Tests

Figs. 16 and 17 show the comparison between the temperatures captured by thermocouples and temperature captured from simulation. To support the research work, two different points on the disk correspondent to thermocouples 1* in the center and 5* at the distance of 80 mm has been processed. These points are chosen because of their relevance in the induction heating of the disk. The profile temperature has been constructed using each point of acquisition both and thermocouple in the correspondent time step.

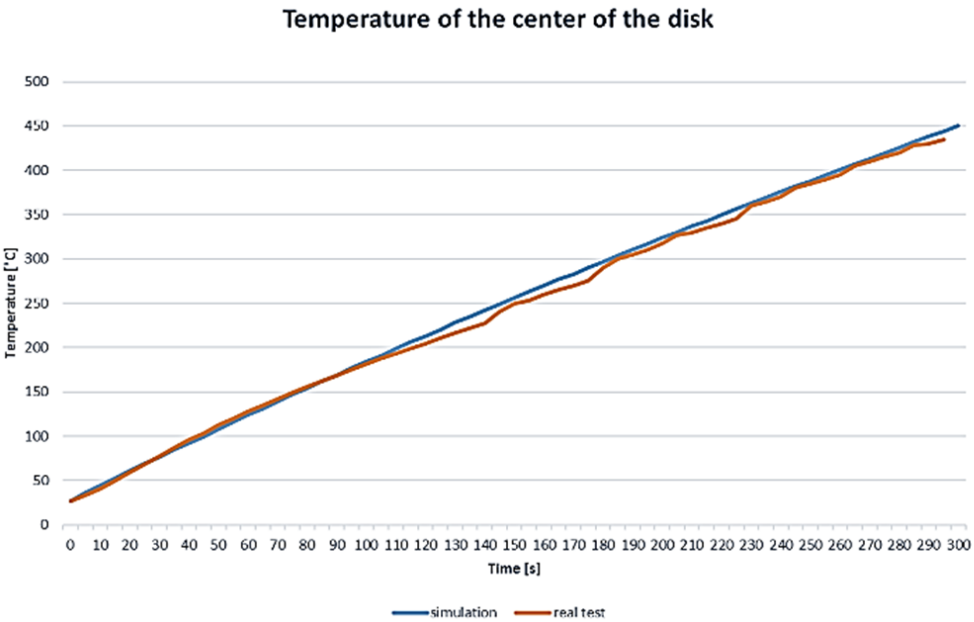

Fig. 16 Comparison between real temperature data on the bottom center of the pot (orange line) and virtual values (blue line) in 300 s

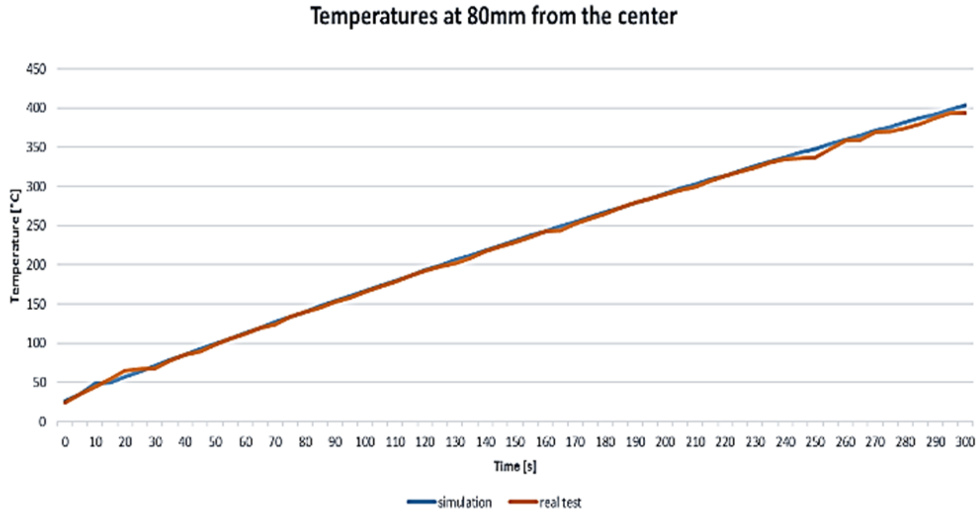

Fig. 17 Comparison between real temperature at the distance of 80 mm from the center of the pot (orange line) and virtual values (blue line) in 300s

The comparison between the temperatures reached by the disk during the simulation and the temperatures reached by the disk during the experimental tests shows a good correspondence of the results and a good correspondence of analysis. However, in the induction hob, the power control implemented in the induction electronics automatically corrects the modulation parameters in order to obtain a constant power supply.

VI. Conclusions

The proposed paper describes a design methodology to support the designer during his/her tasks when he/she has to optimize the performance of a generic mechanical or electromagnetic system. The described approach is generic and can be applied to several component cases; however, this research shows an induction hobs as test case. The aim of this paper is the definition of a flexible methodology able to reproduce the real behavior of product, through virtual prototyping tools. In particular, it is possible to simulate the energy consumption test in accordance to the reference norm. A multiphysics approach has been applied for the analysis and the simulation of both the electromagnetic behavior and the thermal fluid dynamic one. Virtual analyses have been compared with real experiments using FEM and FVM tools with an error less than 5%. Through the analysis of the results, the designers can identify which are the most influential parameters on product performance and consequently make the necessary adjustments. In conclusion, this approach gives a working methodology to the designer in order to achieve a pragmatic study of the operative parameters in the virtual analysis for the reducing of cost and time in the early design phase. As a future development, the proposed methodology could enlarge the number of the parameters analyzed. A different test case such as oven or cooker hood could be analyzed to validate the application of the proposed methodology.

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