INTEGRATED CAE DEVELOPMENT OF INNOVATIVE GRAY IRON HEAT EXCHANGER

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Abstract

The design of industrial component, that will be produced by casting process, can take advantage using traditional structural e/o fluid-dynamic numerical codes (FEM-CFD) in order to optimise the shape and the performance of product. Often, the traditional approach neglects the manufacturing process requirements and the effects of it.

Today, the CAE world offers to the designer a large number of efficient computational codes to create an innovative virtual design chain. Each phase of product development can be analysed starting from the manufacturing process to thermal-mechanic fatigue life.

The paper describes the adopted virtual procedure to develop an innovative grey iron heat exchanger: the thermal efficiency of water and fumes channel has been analysed by the code CFX-5.6; ANSYS 8.0 has been applied to study the thermal-mechanical behaviour in operating conditions; casting process optimisation and residual stresses analysis is the target of MAGMASOFT simulation tool.

The casting process simulation is main key for a foundry company that wants develop a new product, because the process determines the mechanical characteristics of the casting and can influence the definition of innovative heat exchanger with low consumption and high energetic potential.

1. INTRODUCTION

Several opinions assert that the condensing heaters will constitute more and more the reference technology of the future thanks to peculiar characteristics during the working phase: low emission of polluting substances and high energetic efficiency.
The yield of heat generator, which means the ratio between the provided useful energy and the theoretical available energy, can increase using the condensing technology of water vapour as product of methane combustion.
Gruppo IMAR S.p.A., leader in the production and distribution of the pre-mixed condensing heaters, has designed and developed a new version of dual-metal heater, grey iron and aluminium alloy, for domestic use and called " *Bimetal Condens Inka* ", with the following characteristics:

- *modulation range from 6 to 24 kW for heating system and from 6 to 34.8 kW for sanitary fittings*
- *circulatory system with variable flow and thermal gradient of 30 °C*
- *hot water production is in comparison to a 60 litres boiler (16 l/min)*
- *management of different temperatures in two zones*
- *very low emission of noxious substances*

The design of component, that will be produced by casting process, is supported by traditional FEM codes and CFD tools in order to optimise the shape and the performance of the casting, but often the requirements and effects of manufacturing process are neglected.
Today, the CAE world permits us to simulate any single step of the product development starting from the manufacturing process and integrating the best numerical tools to assure the methodology of a virtual design chain.
Generally, different numerical models and corresponding mathematical algorithms are dedicated to each physical phenomena, material behaviour or process to assure robust design and low cost computing. Advanced dialog tools allow to transfer data from a computing program to another one generating a virtual net of integration. Boundary conditions, residual stress-strain states, as well as mechanical properties, can be converted from a control volume grid to finite element model and vice versa.

In the case study of a grey iron heat exchanger, the design chain takes into account two CFD analysis to evaluate the thermal efficiency of fumes chamber and water jacket (CFX 5.6), a thermal-mechanical analysis in working state (ANSYS 8.0) that acquires the residual stress-strain condition at the end of casting process (MAGMASOFT 4.2).
The last aspect have a reasonable importance because the mechanical casting performances, in particular the development of innovative grey iron heat exchanger, depend strongly on the casting process simulation and also from the successive residual stress condition.

2. COMPUTATIONAL FLUID DYNAMIC

The simulation of the fluids, that interact with heat exchanger surfaces, has been divided in two different analysis corresponding to the external surface (boundary condition grey iron – fumes) and the internal surface wetted by water (boundary condition grey iron – water).
The numerical code adopted, as mentioned before, is a general purpose with three-dimensional coupled pressure solver. The fluid-dynamic equations are solved for each cell; in particular, the equation sets corresponds to the three components of momentum, mass conservation and two turbulence laws.

The solution of fluid-dynamic problem, in case of laminar flux with isothermal condition and without chemical reactions, is based on the equation set that represents the conservative and momentum laws, called Navier Stokes. The set is a second order differential equations with the following general form:

$$\frac{\partial(\rho\varphi)}{\partial t} + div\left(\rho\bar{V}\varphi - \Gamma_{\varphi} grad\varphi\right) = S_{\varphi} \tag{1}$$

where is possible to identify the time variation, the convective transport and the diffusion terms, as well as the source element. When the fluid is incompressible, the density is constant, while, if the fluid is compressible, the formulation of perfect gas law can be applied in order to control the density variation.
The Navier-Stokes approach takes into account a turbulent model k-ε (where k is the kinetic energy and ε is the dissipation) while a logarithmic formulation is used for the boundary layer.

2.2. Grey Iron - Water Boundary Condition

The numerical analysis determines the flow path into the water circuit of cross flow heat exchanger to evaluate the heat transfer towards the combustion fumes.
The contact surface between water and metal is spangled with a large number of pins in order to increase the heat transfer. Their location can have effect in terms of:

- increasing of heat transfer surface;
- generating of turbulence in order to increase the heat transfer coefficient and to homogenise the fluid front.

The Iron – Water heat chamber is constituted by a perimetric pipe with a rectangular section cross which conveys the fluid towards the central chamber divided in two sectors with a large number of pins (fig. 1).
The whole domain has been divided with a tetrahedral grid using the TETRA module of ICEM CFD mesh generator, in particular, a refined mesh has been required to represent the pins geometry with more and less 4 millions of total element number (fig. 2).

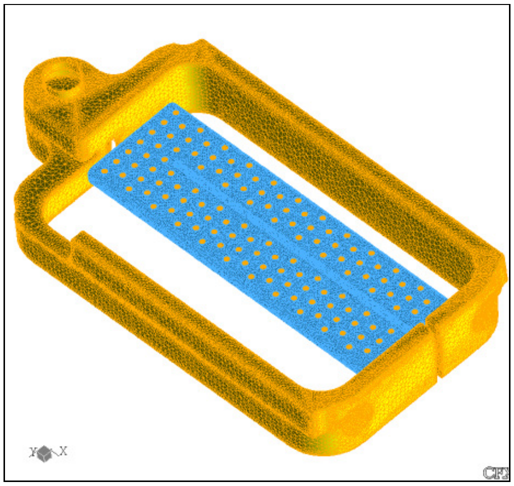

Fig. 1 – Heat transfer surface between Iron and Water

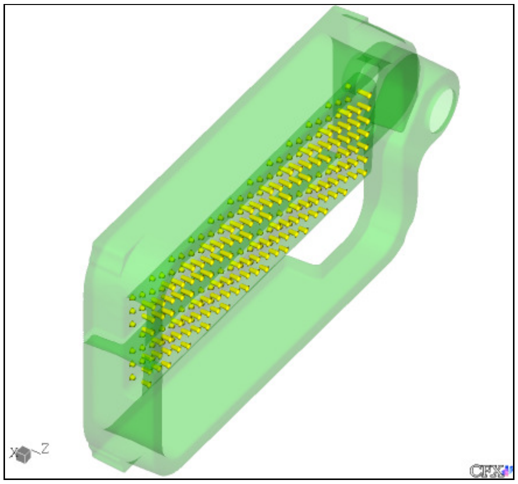

Fig.2 – Mesh of central chamber and pins

The principal input data are the stationary water flow and the null overpressure respect the external ambient.
In general, adding parameters can be useful to describe an interesting aspect called “Fluid Age”, which defines a scalar value of resident time into the heat exchanger (stagnant zones).

The velocity field (fig. 3) shows a longitudinal section with a un-homogeneous flow into the central chamber. It’s clear the effect of stagnant zones where the velocity is lower than its critical value: low fluid velocity have blue colour, while red regions correspond to high value of velocity.

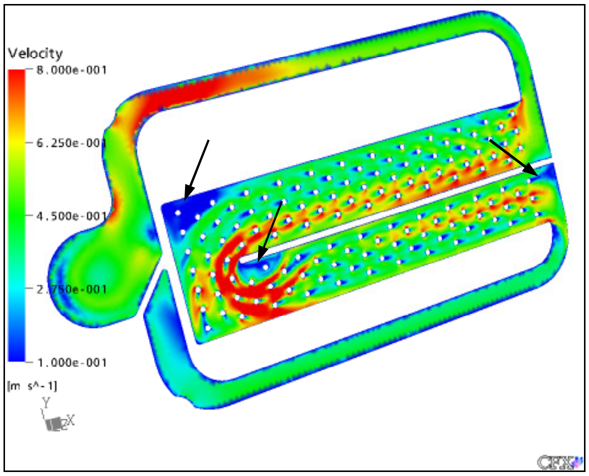

Fig. 3 – Stagnant zones of fluid

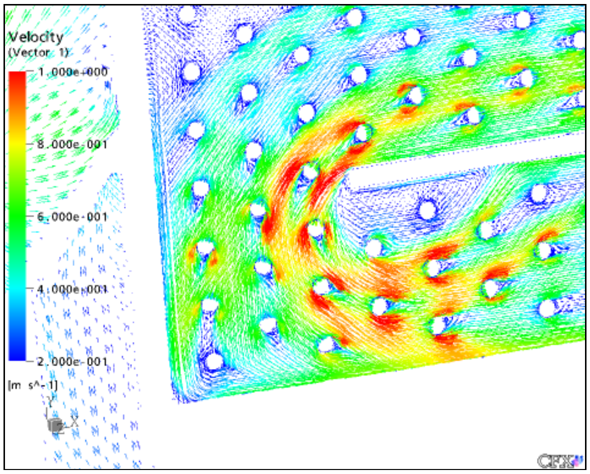

Fig. 4 – Flow path around the pins

The location of pins can be improved to balance the fluid flow close by central septum, as the figure 4 shows.

2.3. Grey Iron - Fumes Boundary Condition

As described before, the standard Navier-Stokes approach has been applied with a turbulence model k-ε (where k is the kinetic energy and ε is the dissipation), adding logarithmic function for turbulent boundary layer.
The strong temperature rate, even though with low velocity value, generates significant density variation of fluid with constant pressure.
Moreover, the radiation heat transfer has been taken into account to consider the effect of high temperature value adopting the ray-tracing (Monte-Carlo) method to calculate the gas radiation on the walls.

An average value of the specific heat has been assumed at constant pressure based on flow and fumes composition, while the thermal conductivity is function of temperature variation.
The thermo-physical iron properties, in terms of heat capacity, density and conductivity, cannot be assumed as constant because the temperature range is about 900 °C when it is in contact with the water.
Different heat transfer coefficients (HTC) and bulk temperatures have been defined corresponding to the boundary water conditions (wall- water1 and wall-water2). In particular, the first zone represents the surface with pins and high heat transfer, while the second one is the remaining circuit. Besides, the bulk temperature of second zone is the greater because the water goes out.
The heat transfer coefficients have been estimated by a formulation based on Reynolds number in a medium section considering the radiation contribution due to the high temperature value at the inlet. Typically, the absorptivity of combustion products (water vapour and carbon dioxide), which means the fraction of absorbed radiation heat, can be about 40-50% of total radiation energy.

The results analysis can describe the flow path and the pressure distribution in three o more sections of the model (fig. 6), as well as enthalpy balance and temperature distribution of the grey iron component (fig. 5).

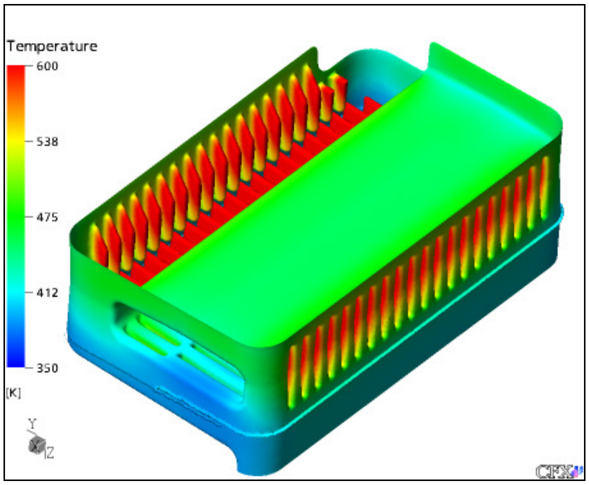

Fig. 5 – Temperature distribution of grey iron surface

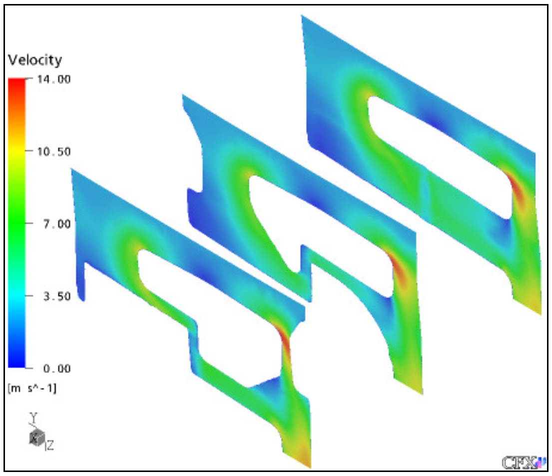

Fig. 6 – Velocity distribution of three sections

3. THERMAL-MECHANICAL ANALYSIS

The grey iron heater, unlike aluminium alloy heaters, is subjected to maximum thermal rates due to the direct contact with the burner flame controlled by ignition system.
The scope of thermal-elastic analysis is the determination of maximum and minimum values of temperature during the working phase of exchanger. The maximum stress condition happens when the water is at operating condition for temperature and pressure and the hot fumes invest the heater; while the minimum stress condition is obtained when the heat exchanger is in thermal equilibrium with the water.

The results of the CFD analysis, as described before, are the boundary conditions of the thermal-elastic response of the heat exchanger in terms of pressure, temperature distribution and heat transfer coefficients. Therefore, the CFD results are the input variables of structural analysis and the connection of CFX and ANSYS code is the key for a new step towards the design chain (fig. 8).

A steady-state thermal analysis, based on tetrahedral finite elements with 10 nodes and quadratic shape functions – SOLID87 (fig. 7), permits to evaluate the temperature variation in the wall thickness starting from the CFD boundary conditions. The heat transfer coefficients have been defined on the iron-fumes and iron-water surfaces using SURF157 elements. Obviously, the water pressure load has been considered on the inner surface.

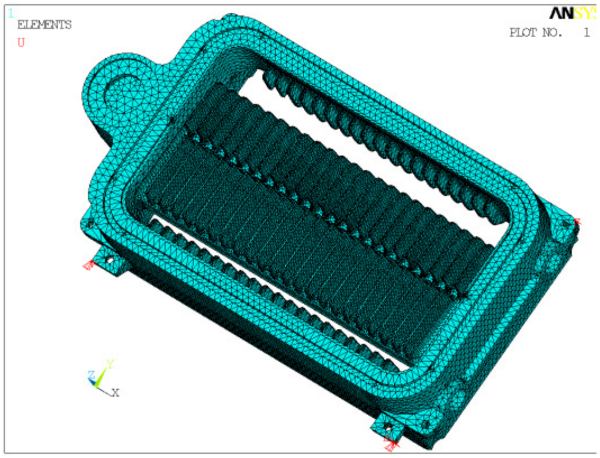

Fig. 7 – FEM mesh and constraints

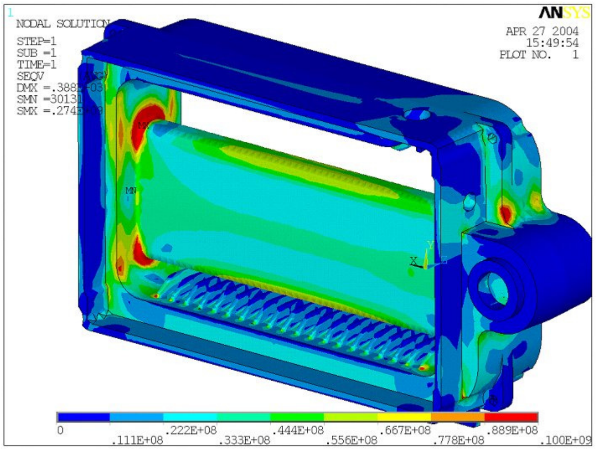

Fig. 8 – Temperature distribution of iron-fumes surface

The static response shows a strong influence of temperature field on stress-strain distribution, in particular at the connection zones of the central region with the external pipe.

The study is extremely interesting because it permits to point out the stress critical points (fig. 9) of the body and estimate the thermal fatigue life of the component.

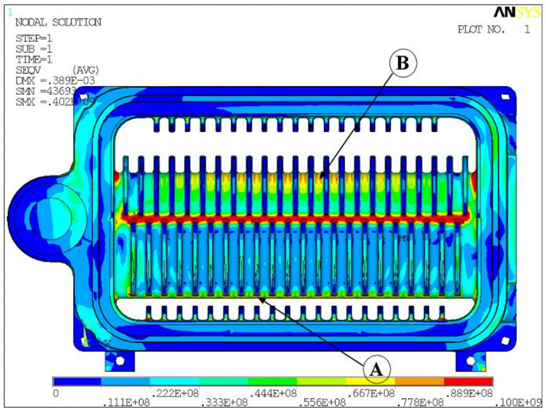

Fig. 9 – Von Mises equivalent stress and some critical points

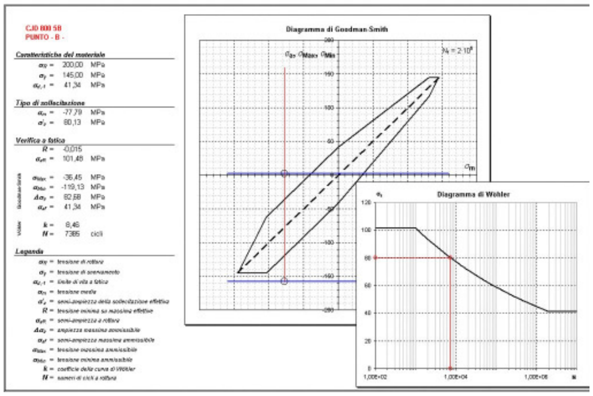

Fig. 10 – Fatigue test of point B using Goodman-Smith diagram

Finally, the fatigue response can establish the number of necessary cycles to obtain the body collapse based on the Wöhler curves for the mentioned extreme loads (fig. 10). The three-axial stress problem has been treated assuming the Von Mises equivalent stress as the reference one, which conventionally assumes positive values for tensile state and negative sign for compressive one.

4. FOUNDRY PROCESS OPTIMISATION

The casting process is one of the most attractive and efficient manufacturing method to create complex shape products with high production rate and low cost.

The good castability of grey iron and its thermo-physical properties are ideal characteristics to produce heater, with tongues and pins, using a line with eight compacted sand moulds in an automatic implant (fig. 11).

The production rate can grow with simultaneous casting for two components, but this method can introduce further variables that complicate the optimisation project.

The pouring temperature and the balanced fluxes into the two cavities determine the melt temperature distribution during the filling phase. The filling process should be concluded in reasonable short time in order to avoid cold shuts or unsuccessful filled zones. The casting quality depends on, besides these macro-defects that are index of scraps, the possible oxidations and the grain inclusions due to turbulent flux and surface erosion of the sand mould.

The main objectives of optimisation casting process, supported by simulation tool, are the prediction and minimisation of filling defects as well as the system design to guarantee the feeding of solidification shrinkage (fig. 12).

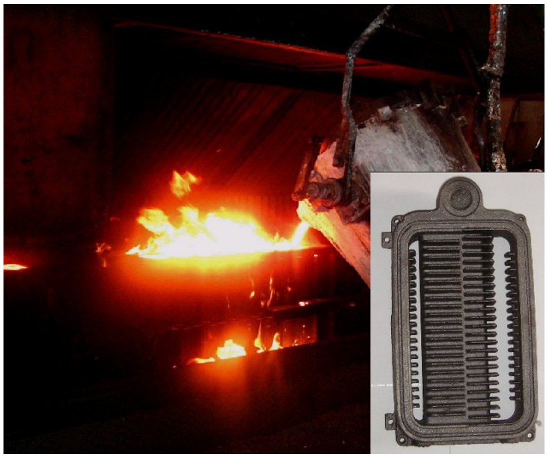

Fig. 11 – Foundry iron process

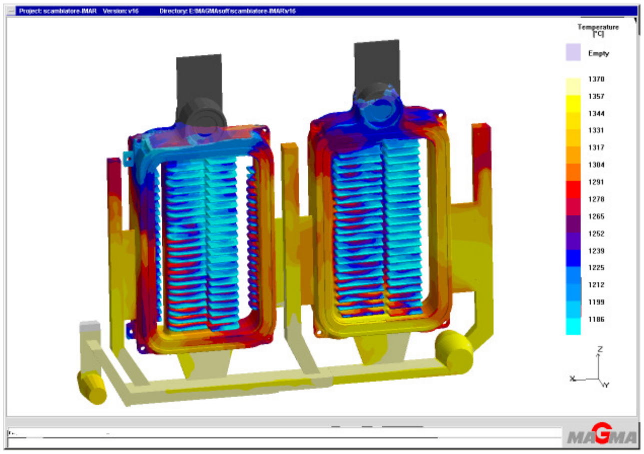

Fig. 12 – Temperature distribution during filling simulation

The MAGMASOFT simulation tool, based on Control Volumes grid with Volume-Of-Fluid (VOF) model for the free surface movement [1], includes also a micro-modelling algorithm in order to simulate the real feeding behaviour taking into account the graphite expansion, that permits to cast heaters without risers using grey iron material.

In case of similar thin-walls components, the solidification path of iron casting depends on temperature distribution at the end of the filling (fig. 13) and promotes the grey iron eutectic growth and corresponding morphology. The cooling-rate during the solid-state transformations is the prime importance for hardness of pearlite and for general mechanical properties.

The new design of gating system and the elimination of casting defects were the main goals of Gruppo IMAR foundry to improve the production rate and casting soundness validated by experimental investigations in terms of micro-structure and mechanical properties data.

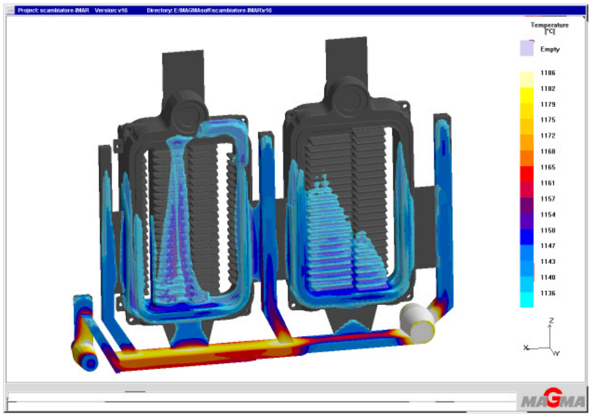

Fig. 13 – Solidification simulation

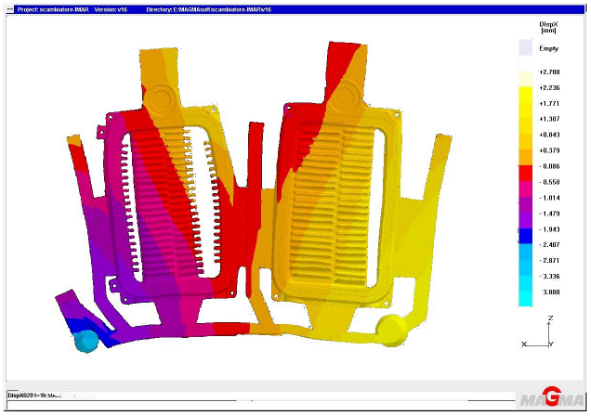

Fig. 14 – Residual stress-strain response

5. RESIDUAL STRESS ANALYSIS AND CAE INTEGRATION

The main activity of the company is not only the foundry process for heat exchanger; in fact the product is machined and assembled to create the a "Ceramic Compact" condensing heater.

The foundry product, even though it is a net shape casting, suffers the consequences of residual stress-strain re-distribution during the machining of gating system.

The residual stress state, due to un-homogeneous solidification time (fig. 14), presents a tensile stress in the last solidification regions, in particular on its surface, because its contraction has been limited by high stiffness of the previous solidified regions [2].

The study of this unloaded state must follow the real production method but, in spite of the use of dedicated simulation tool, the optimal design is hardly to find in particular for complex shape casting with tongues and different connection radius.

Some improvements, excluding modifications of optimised process parameters, have been obtained from thickness and dimension variations of tongues in contact with fumes.

The new shape have to assure the energetic efficiency of heater, as predicted by CFD simulations, as well as to reduce the values of residual stresses that can play an essential role for fatigue life time of the product.

The virtual procedure follows the production methodology transferring the mentioned constraint state to the FEM numerical model able to simulate the thermal-mechanic fatigue life (fig. 15-16).

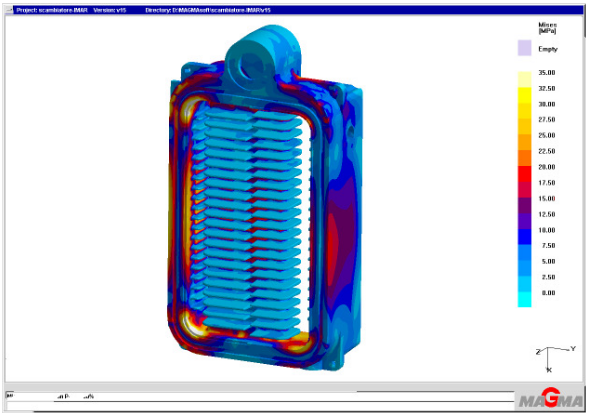

Fig. 15 – Residual Von Mises stress in MAGMASOFT

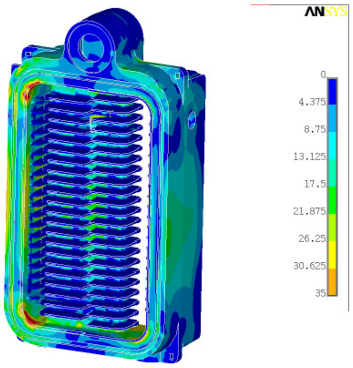

Fig. 16 – Residual Von Mises stress transferred in ANSYS

The Control Volume grid is substantially different from tetrahedral Finite Element mesh due to the huge difference of nodes as well as their distribution on three-dimensional computational domain. MAGMAlink is a tool that permits the interpolation of data and each result can be transferred to other codes; in our case study, the tensile tensor has been converted to ANSYS. The interpolation method requires an accurate evaluation of its errors and their minimisation, but it is the more important step to connect the production with the working phase of the component.

6. CONCLUSIONS

In spite of many simulation techniques have demonstrated their capability in specific application fields, many other virtual design procedures are emerging based on multidisciplinary CAE integration in order to accurately pursue the product development [3].

This innovation is recognised as a winning arm to amplify the knowledge base as well as to improve the competitiveness of a new product that satisfied the customer requirements [4-5]. 3D models and simulation tools have impact on the design costs but they allow to optimise the manufacturing process as well as to reduce testing phase.

A scenario of these simulation technologies has been presented with the industrial case application of a grey iron heat exchanger, in order to evaluate their impact in the design chain and within the company organisation.

The integrated approach of CFD, FEM and Casting Process simulation, thanks to dialog windows between different numerical methods, is possible and permits to virtually develop a prototype with optimal geometrical characteristics and improved operating performances, and also to predicts the fatigue life response.

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