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CFD modeling in Industry 4.0: New perspectives for smart factories

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Abstract

Industrial market is becoming increasingly competitive and companies need even more advanced resources to advantage over competitors. As an example, simulation is part of Industry 4.0 technologies and a key tool for lay out re-configuration, in order to realize a flexible product customization but also to optimize manufacturing processes. For these reasons Computational Fluid Dynamics (CFD) simulation can determine a competitive advantage for smart factories in the light of possibilities offered by new technologies.
The research is focused on a conceptual solution to integrate CFD simulation with technologies of the Industry 4.0, in order to open new opportunities for companies in terms of in terms of growth and competitiveness.

Keywords: Computational fluid dynamics, Industry 4.0, Simulations, Smart Factory, Manufacturing reconfiguration, Big Data

1. Introduction

In the current industrial market competition, companies have to adopt innovative strategies to predominate over the other competitors. In modern manufacturing, product customization is increasingly becoming more prevalent, time to market is reduced and companies have to address to the market fluctuations with a quick response in terms of flexibility and re-configurability of manufacturing systems [1-6]. In addition to these aspects, some industrial sectors, in particular food and pharmaceutical, have constant changes in layouts to meet stringent hygiene, health, and safety legislations [7].

In this scenario, we believe that some Industry 4.0 technologies can provide benefits to companies in terms of higher flexibility, responsiveness and costs savings. For such purposes, we identified the computer simulation and, in

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particular, Computational Fluid Dynamics (CFD) simulation as the tool that, more than others, can potentially increase its importance and weight in Industry 4.0, being even more effective to support manufacturing management.

According to [8], "Computational fluid dynamics (CFD) modeling provides an alternative way to investigate fluid flow in complex geometries. It complements experimental work with less cost. CFD is defined as the analysis of a system involving fluid flow, heat transfer, and mass transport and related chemical reactions using computer-based simulation. This branch of fluid flow analysis complements experimental and theoretical work, providing economically interesting alternatives through the simulation of real flows and allowing an alternative form for theoretical advances under conditions unavailable experimentally".

Simulation is a digital tool that can support the design and management of manufacturing systems and is one of the nine technologies of for developing the Industry 4.0 program [9,10].

Simulation can be considered complementary to Industrial Internet of Things (IIoT), Big Data Analytics and Clouds [10,11-16]. IIoT and Cyber-Physical Systems (CPSs) enable the interconnections of physical objects by sensors [10,17], making possible to exchange global or local data. On the other hand, Clouds and Big Data Analytics allow to handle and analyze data to support real-time decision making [10,16,18]. Simulations are involved in the so-called "value networks" and allow the optimization of data from intelligent systems [19].

According to [20], "the development of virtual models, also referred to as digital twins, of industrial systems opens up a number of opportunities, such as the use of data to anticipate the response of a system and brainstorm malfunctioning, and the use of simulations to develop new technologies, i.e. virtual prototyping". A definition of digital twins is also given by [21], in which it is said that it is "an integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by digital thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin".

These technologies create an industrial network, bringing to the creation of the smart factory [22]. In particular, the algorithms that are behind data analytics and simulations represent the "intelligence" of a smart factory, providing solutions and corrective actions [23,24].

This paper aims to give a conceptual solution to integrate CFD simulation with technologies of the Industry 4.0 basing on the technological state-of-art and provides a comprehensive framework for understanding key elements for innovative CFD simulation solutions in an Industry 4.0 context and related advantages.

2. CFD simulation in smart factories

The fluid dynamics plays a critical role in many engineering applications, these include: (i) heating, ventilation and air conditioning of buildings; (ii) combustion in boilers or propulsion systems; (iii) interaction of various objects with the surrounding air-water or air-particles mixture; (iv) complex flows in heat exchangers and chemical reactors.

In this scenario, two main application categories can be conceptually identified: air ventilation and air conditioning. Air ventilation involves the optimization of air velocity and temperature for a specific industrial process, moisture content, particles and contaminant distribution or dispersion of a particular gas. Air conditioning concerns operators' health or advanced manufacturing process (food or pharmaceutical industry) that demand particular operating temperature and air quality for conservation of semi-finished products or machines.

In the literature there are several examples of CFD simulations to investigate ventilation and conditioning inside a factory. In [25] is used CFD to simulate airflow of a clean room for hard disk drive factories in order to reduce the contamination of particles in the automatic machinery. In particular, the simulation shows the airflow in every area inside production line, for an optimal machine layout. In [26] is studied the ventilation performance in factories by using CFD and they predict the flow field and particle distributions considering complex layouts. According to [26] and [27], simulations for air conditioning prediction is important for operators' health in terms of temperature distribution in work environment and the quality of inhaled air. In [28] is used CFD as analysis technique for predicting gas explosion on a control room for oil and gas industry. According to [29], it is possible to apply CFD technique for heavy gas dispersion modelling, with results validated against experimental data in terms of concentration. The optimization of a ventilation system using the CFD model is often required, in fact an effective ventilation is critical for improving indoor air quality and reducing occupant exposure [29]. Furthermore, several studies [7,30-32] consider CFD simulation as a promising tool for ventilation design in food factories.

The manufacturing industry can take advantages from CFD simulations for a variety of reasons. Reconfigurable manufacturing systems need frequent change in machine layout and CFD helps to understand in advance the air flow and temperature in every area of the factory. In addition, it helps both machine and human health to work with proper operating conditions. The production can be increased through a quicker and more effective design of processes and machines. Finally, Augmented Reality allows to visualize the results of CFD analysis in real environments and this can help maintenance tasks [33,34], knowing in advance pollutants and temperature. Fig. 1 shows an overview of main CFD applications and their effects on manufacturing management.

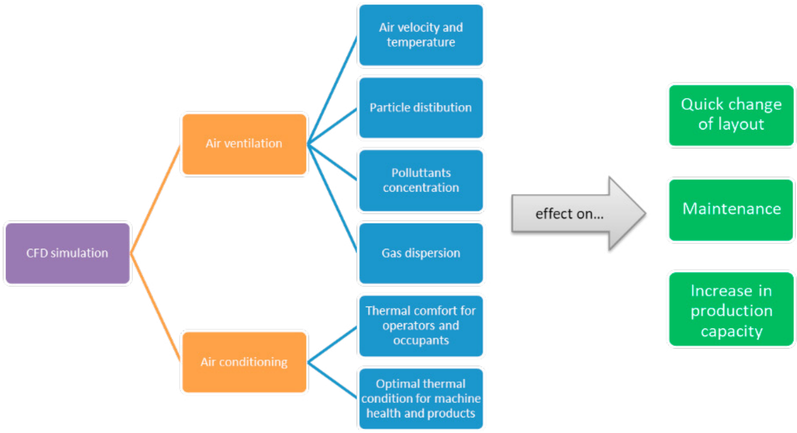

Fig. 1 – Overview of CFD simulation advantages for a factory.

3. CFD simulation workflow

In engineering applications, differential equations that describe the three-dimensional motion are solvable with numerical methods. Governing equations are then discretized in space and time and solved with suitable algebraic techniques, which are implemented in a CFD code (Computational Fluid Dynamics).

The numerical solution for a partial differential equation is based on finding the value of the dependent variable ϕ in a specific point of interest in the discretized domain [35]. CFD can be defined as the set of methodologies for the simulation of fluids flows, predicting heat and mass transfer, phase change, chemical reaction, fluid structure interaction and particle dispersion and evolution [25,36-40]. CFD is also a general method of investigating ventilation performance and thermal environment in factories [26].

Fig. 2 shows the CFD simulation workflow that consists in three basic steps, that are: pre-processing, solving and post-processing. The modeling of a physical phenomenon takes place during the pre-processing phase [41]. A physical phenomenon can't usually be considered fully understood until it is possible to formulate it in mathematical terms, and this formulation should be tested and validated. In a numerical analysis procedure, two subsequent modeling levels are taken into account: the "geometry modelling", that is the modelling of the physical domain's geometry, and the modeling of the physical process itself. The "mesh generation" is the discretization of the geometrical domain and is based on the generation of a numerical grid that is used to solve numerically the governing (model) equations. The subdivision of the domain in cells consists in a certain number of non-overlapping and mutually interconnected elements.

During the "physical model definition", the physical model that describes the phenomena behavior is established and the algebraic equations are discretized according to information related to the considered topology. The topology consists in a series of information needed for understanding how cells are positioned in relation to each other. During some discretizing method (i.e. Finite Volume [35]), the differential equations are integrated for each element of the mesh, resulting in a set of algebraic equations in the same number of the grid's nodes. The algebraic equations are then assembled in matrixes and vectors, by means of two consecutive passages, i.e. the local assembly in which the single equation is built, based on the considered node and its neighbor nodes, and a global assembly for all the equations, that consists in the set-up of the matrixes and vectors where each row and column is defined based on the position of all the nodes in the computational domain (element connectivity).

The resulting algebraic system can be expressed as the following form: A[T]=b. Where [T] is the column vector of the generic unknown variable T to be assigned to computational nodes, A is the coefficient matrix and b is the vector of the known terms. The algebraic system allows to know the generic physical quantity in each point of the domain and during the post processing phase it is possible to visualize, interpret computational fluid dynamics data and compute them.

The “solving stage” is composed by four main steps in that “transport equations” are solved, “physical models” and the “solution setup” are set, and, finally, “solver settings” are appropriately configured.
During the final “post-processing stage”, numerical results are interpreted and displayed.

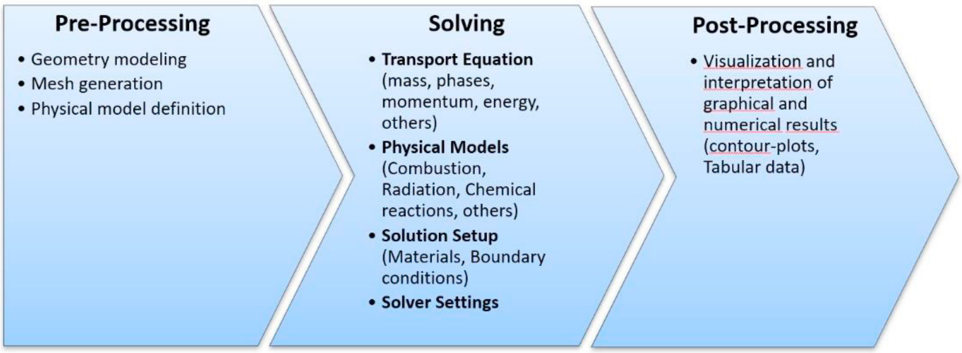

Fig. 2 – CFD workflow.

4. Key elements for innovative CFD simulation solutions in industry 4.0

Conventional conception of CFD simulation can be turned from three Industry 4.0 aspects that are: Cloud Computing, Augmented Reality (AR) and, in general, the opportunity to handle a continuous “digitalized” data flow.

In [42] is underlined that CFD simulations have a computing time that strongly differs from production processing time but Cloud Computing can overcome this problem. In fact, it includes on-demand computing resources that provides computing resources (e.g., networks, servers, storage, applications, and services), which can be easily provisioned from users and enterprises with various demands in computer capabilities [16]. For example, Amazon Web Services provides “CPU, GPU, and FPGA servers on-demand, optimized for specific applications, and without the need of large capital investments” [43]. On the other hand, a “digital” factory can simplify simulation providing data in digital form. For example, it is expected that the geometry of factories or 3D models of objects that compose the layout are stored in a digital form that can be handled by conventional CFD softwares. At the same time, we have available digital information about operating parameters of machines (e.g. flow rate, temperature) from CPSs sensors and all physical boundary conditions stored in Big Data database. The availability of this data is fundamental for a quicker pre-processing phase (described in section 3). Visualizations of CFD results can be directly processed using softwares for Augmented Reality and then interpreted using a conventional smart device, as tablet or wearable [34]. Fig. 3 shows an overview of main actors involved in simulations process.

Main advantages of CFD simulations can be resumed in four main points [35,41,44,45], that are: 1) cost reduction; 2) fast response to design variations; 3) thorough information and 4) the possibility to simulate different conditions. The cost reduction is achievable because to perform simulations is generally cheaper than physical experiments and tests. The fast response is due to the relative low time that some simulations demand and the possibility to easily extend the same solving asset to different engineering data. If compared to experiments, where data can be extracted only from a limited number of sensors, simulations give always information for the whole domain. Finally, CFD can theoretically simulate any physical condition.

On the other hand, critical aspects of CFD simulations are mainly related to errors that can occur for simplified flow models and boundary conditions or interpolation errors. Furthermore, the computation time can be relevant for large domains.

In order to address future challenges in CFD simulations, it appears evident how ever more highly efficient numerical methods are demanded, in particular they should be able to handle intricate geometries, as well as to resolve complex flow aspects. Finally, the automation in the workflow represents a key element for reducing both time and human error possibilities.

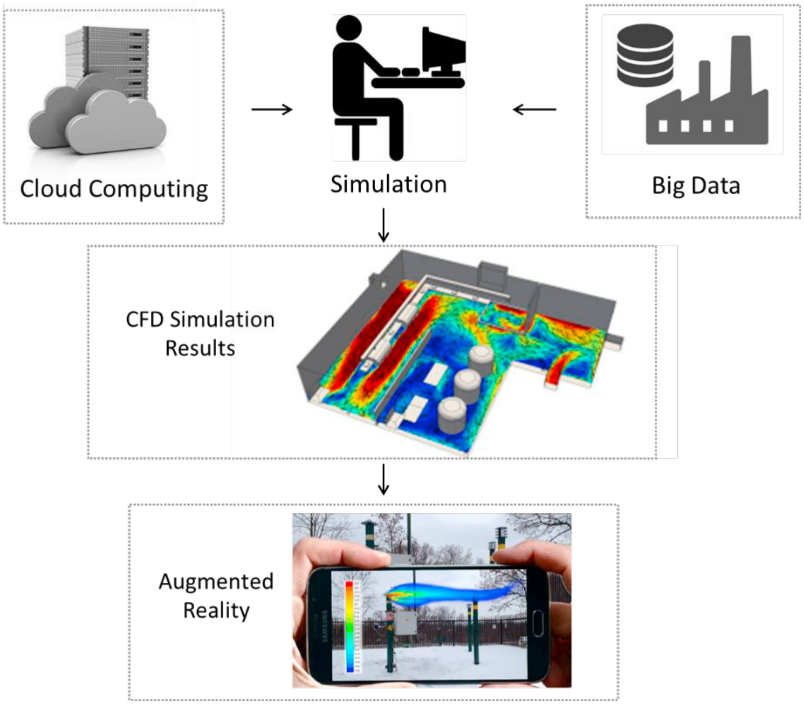

Fig. 3 – Overview of technologies and key elements for CFD simulation in Industry 4.0. Source: Authors' elaboration, [34,46].

5. Conclusions

The industrial market becomes every day more competitive, companies need innovative strategies for reducing time to market. Simulations can help for a re-configuring layout in order to realize a flexible product customization and a manufacturing processes optimization. Simulations are part of the Industry 4.0 technologies and are a key tool for re-configure layout in order to realize a flexible product customization but also optimize manufacturing processes. We conceptually identified two main application categories for CFD simulations: air ventilation and air conditioning, with a large number of examples found in literature. Technologies of Industry 4.0 can be integrated in order to realize innovative uses of simulation results. For example, Augmented Reality allows to visualize the results of CFD analysis in real environments and this can help maintenance tasks.

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