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Converting a food oven into a thermal sanitizer for Personal Protective Equipment against COVID-19: Computational Fluid Dynamics simulation

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Abstract

COVID-19 brought several management problems, and among these surely the topic of Personal Protective Equipment (PPE) turned out to be crucial. Indeed, in the light of mandatory measurements adopted by governments both for private individuals and companies, their demand has rapidly increased, thus generating shortages, increased waste and unbalanced prices. In response to that, many industrial fields offered their tools and know-how for trying to partly face this issue, and in this paper part of a solution of this kind is presented. Specifically, it is meant the redesign of a food oven produced by an Italian company operating in the food sector (Nilma S.p.A.) for thermal sanitization against the virus in question. In this paper, the simulation of the temperature distribution inside the chamber is simulated, with subsequent experimental validation at 95°C.

Keywords: Computational Fluid Dynamics – CFD, Simulation, Temperature Distribution, Food Industry, Disinfection.

1. Introduction

Among the main issues addressed by the recent COVID-19 pandemic which affected the entire world in 2020, surely the topic of Personal Protective Equipment (PPE) deserves attention. According to Cook (2020), two main problems emerged: the shortage of the equipment, and its inappropriate use, which quite often results in items intended for single use being reused or worn for longer periods than recommended (Kasloff et al., 2021), probably as a consequence of the first problem highlighted.

Moreover, this issue can also be seen under a sustainability point of view, declined in its three pillars: as far as the environmental perspective, equipment must be disposed of in a proper way thus generating increased waste (Liand et al., 2021), and produced as well; regarding the economic side, the price of the equipment has to be affordable and accessible, above all if we consider that many governments mandated the use of masks by the general public thus forcing people to purchase them (Zimmerling and Chen, 2021); finally, the social dimension is involved as well, since PPE must be indistinctly guaranteed for all, regardless country or income, since this situation affects the whole world.

If we think that the demand for PPE is not expected to decline during the post-pandemic period, but is rather estimated to increase 20% up to 2025 (World Health Organization, 2020), it follows that some actions may be adopted and developed, in order to face a continuous and growing demand, with subsequent consequences which could derive (e.g. repeated eventual shortages, increase in waste or in spending from private individuals but also companies which must guarantee PPE for their workers).

In the light of these premises, the study here presented is part of a main project which involves the Department of Engineering and Architecture of the University of Parma and a company based in the North of Italy, Nilma S.p.A. (https://nilma.com/eng), which produces machinery for the food sector, whose aims is to develop a machine for the thermal sanitization of disposable PPE. This is a shining example of the efforts that several industrial fields did in order to respond to different needs arose from the COVID-19, with the tools and knowledge they own. Specifically, in this case, the food context is involved, thanks to a simple food oven.

In literature there are just few evidences of thermal treatments on the SARS-CoV-2 virus for sanitizing PPE, surely due to the novelty of the topic. From a brief analysis carried out by the authors, what in general emerges is that completely disabling the virus in question requires between 30 and 60 minutes, at a temperature of 65-75°C, clearly depending on the boundary conditions. In support of that, it is worth mentioning the recent studies by Celina et al. (2020), Xiang MB et al., (2020) and Fischer et al. (2020). Note that all the papers dealing with thermal sanitization on PPE tested face masks; in the present manuscript, instead, the PPE under investigation is the white coat.

The part illustrated in this paper deals with the simulation of the temperature distribution inside the chamber (a Computational Fluid Dynamics - CFD simulation), made through the software Ansys© (https://www.ansys.com), and the comparison with the subsequent real distribution (i.e. the experimental validation) recorded thanks to a testing session.

The reminder of the paper is structured as follows: section 2 provides a brief description of the machine, as well as the simulation and validation procedures; section 3 illustrates the simulations outcomes, together with the experimental validation. Finally, conclusions and future research directions are provided in section 4.

2. Methodology

2.1. The machinery

The machinery, entirely made of stainless steel, is designed so as to be able to host specifically up to 11 white coats, properly distanced among them and the insides. The sizes of the chamber are 1,693 x 1,010 x 670 millimeters. Hygienic design criteria were adopted in the development.

The machinery (shown in Figure 1) is equipped with:

- relative humidity sensor, able to assess the different saturation level within the chamber;
- double temperature sensor in order to monitor the temperature of the PPE and of the outlet air produced by the heater;
- electric steam generator (relative pressure set at 0.2 bar, safety valve at 0.5 bar), including resistors as the chamber is supposed to work in a dry environment as well;
- fans system, able of processing a 2,256 m^3/h flow rate;
- control panel (touch) for letting the operators interact with it and set the desired parameters (temperature, humidity and treatment duration).

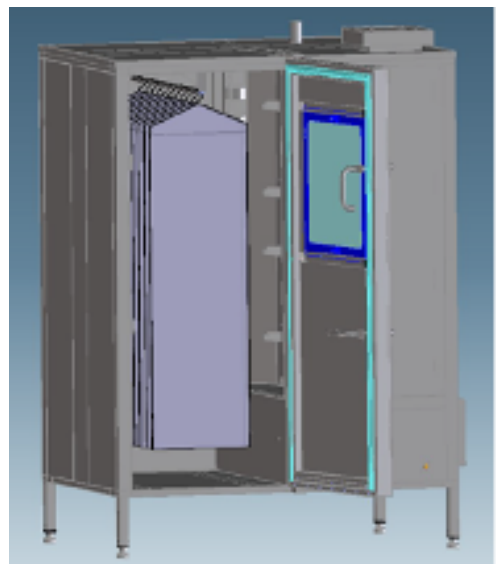

Figure 1. The machine for thermal PPE disinfection.

2.2. Simulation procedure and assumptions

As already stated in the introduction section, the software Ansys was involved for the CFD analysis.

Using a parametric three-dimensional drawing software, we selected the parts to be involved in the simulation (chamber and white coats). After isolating them, the negative of the full chamber was recreated, i.e., the volume involved in the CFD simulation.

By using Ansys, it has been assumed a thermal exchange by convection through the external walls (the insulated ones of the machine), and adiabatic conditions both in the surfaces of the white coats and in the wall that includes the air inlet and outlet slots. A denser mesh was created near the white coats (points of interest) and a sparser one in the rest of the chamber (including the edges).

The assumptions made during the development of the model are the following:

- Initial chamber temperature: 20°C;
- Set-point temperature of the white coats: 95°C (without transient, steady state conditions);

- Set-point temperature of the outlet air produced by the heater: 105°C (without transient);
- Rigid, immobile white coats that do not exchange heat;
- Simplified air inlet and outlet surfaces;
- Supply air flow speed: 7.5 m/s (reparametrized to simplified inlet surfaces).

Note that despite from literature, as already stressed in the introduction section, the SARS-CoV-2 virus should be destroyed at a lower temperature, the choice has fallen specifically on the value of 95°C in order to test the pilot plant's chamber insulation, since the higher the temperature, the higher the heat dissipation.

2.3. Validation procedure

In order to experimentally validate the CFD simulation, several thermal cycles were carried out in May 2021 with a full machine, and the temperature was monitored at different points in the chamber.

Fifteen EasyLog Cold Chain sensors from Lascar Electronics (see figure 2), which can withstand high temperatures and high degrees of humidity, were involved for monitoring the temperature. These sensors are attached to the white coats inside the chamber, most of them at the bottom. The reason for chosing this location is that the bottom is the coldest zone of the chamber and accordingly the most critical one, as also the simulation highlighted and as it was inferable from the heat behavior itself, which rises temperature in the ceiling area. Then, once connected to a computer, they provide the temperature trend over time (using a specific proprietary software).

Figure 2. EasyLog Cold Chain sensor.

The abovementioned software used for importing data collected from the sensors is EasyLog CC (from Lascar Electornics as well, freely available at the following link: https://www.lascarelectronics.com/software/easylog-software/easylog-cold-chain), whose initial interface, shown in Figure 3, allows to initialize the sensors for new sessions, to save the collected data and to obtain graphs showing the historical trends of the measurements (e.g. time/temperature or time/humidity).

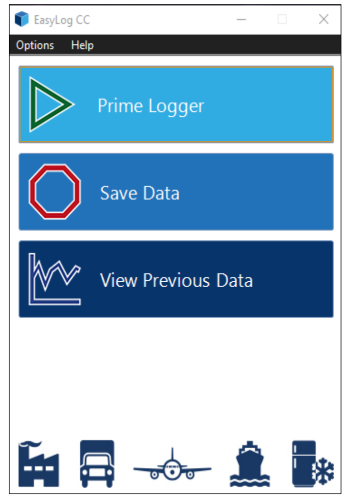

Figure 3. EasyLog CC software interface.

Figure 4, instead, presents the distribution of the sensors inserted within the chamber at the basis of the white coats. Actually, sensor #1 was damaged during the first test, and according to that it was removed, and the final number of sensors involved for tests is then fourteen.

Twelve sensors were put on the lower side of six white coats, as shown in the figure. Specifically, on the two white coats closest to the door (i.e. sensors #12, #13, #14 and #15), on the two at the opposite side (i.e. sensors #2, #3, #4 and #5), and on the two occupying the intermediate position (i.e. sensors #8, #9, #10 and #11).

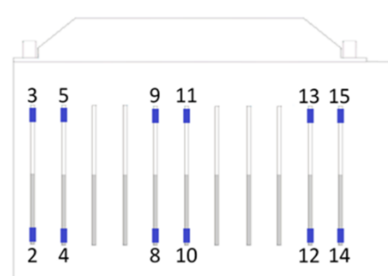

Figure 4. Map of the twelve sensors inserted within the lower zone of the chamber (plan view). Note that the door is on the right side of the figure.

Moreover, for completeness, two sensors, i.e. #6 and #7, were positioned at the top of the intermediate white coat, just as a control of the upper temperature (Figure 5).

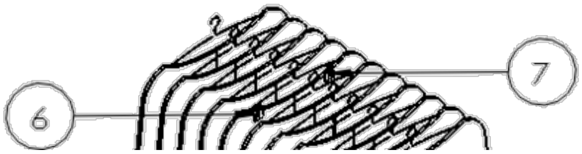

Figure 5. Positioning of sensors #6 and #7.

The temperature distribution at steady state was then compared with that previously obtained from the simulation, so that the correct functioning of the machine could be verified.

At the same time of these test, physical tests were carried out as well, in order to assess whether the mechanical properties of the materials constituting the PPE were damaged as a consequence of the thermal treatments or not.

3. Results

3.1. Simulation results

The simulation resulted in air speed and temperature distributions under steady conditions.

Figure 6 below firstly shows the flows trajectories and their velocities as obtained from the simulation, from which we can deduce a certain uniformity.

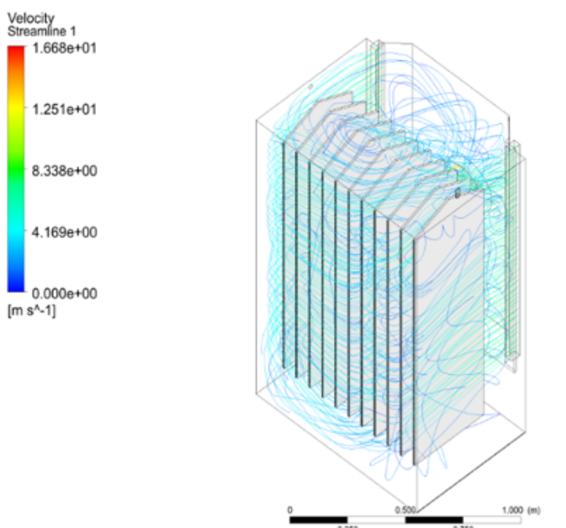

Figure 6. Velocities inside the chamber, obtained through the simulation.

However, by observing in plan (Figure 7), an unexpected behavior is highlighted.

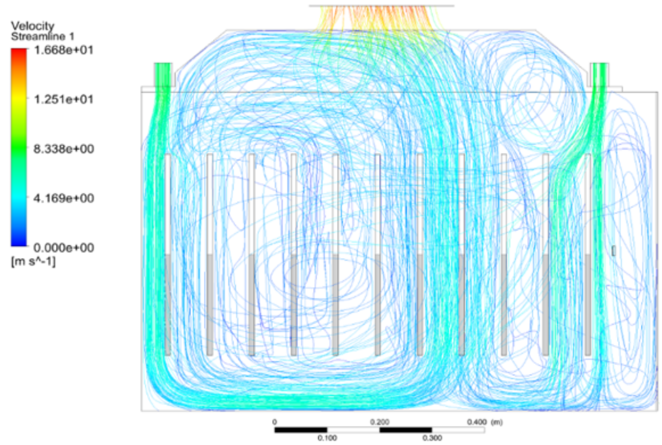

Figure 7. Velocities inside the chamber, obtained through the simulation, in plan.

Indeed, the resulting distribution is asymmetric, showing unbalanced flows. This is actually due to the fact that the pattern of white coats is not symmetric as well as the chamber geometry, and it can be noticed that on one side, namely the right one in Figure 7, the airflow dissipates more energy due to the direct impact on a coat.

As far as the temperature, instead, from the resulting distribution shown in Figure 8, it can be immediately deduced that the extremities of the white coats are subjected to higher temperatures, due to their proximity to the supply flow, and that, in general, within the core of the chamber the temperature never falls below 89°C. There are areas in which the heat exchange is actually lower, but this difference is neglectable, given the high temperatures involved.

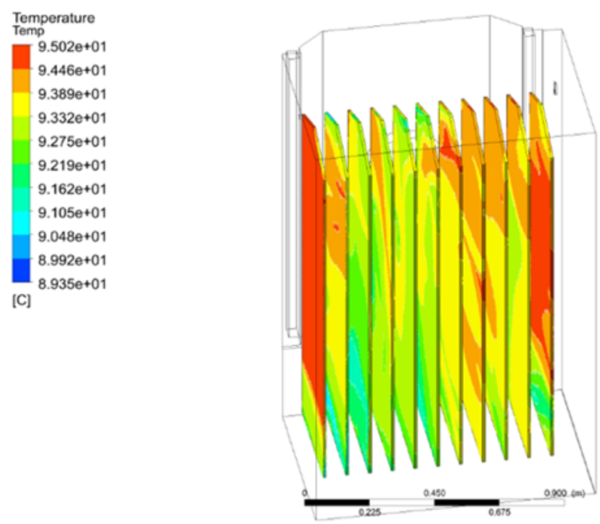

Figure 8. Temperature distribution inside the chamber, obtained through the simulation.

By analysing the trend on the set section planes (Figure 9), we can state that the chamber has an almost constant temperature: in the heart of the machine the set-point has been reached and the gradients only occur near the walls set as external and, therefore, where there is exchange by convection.

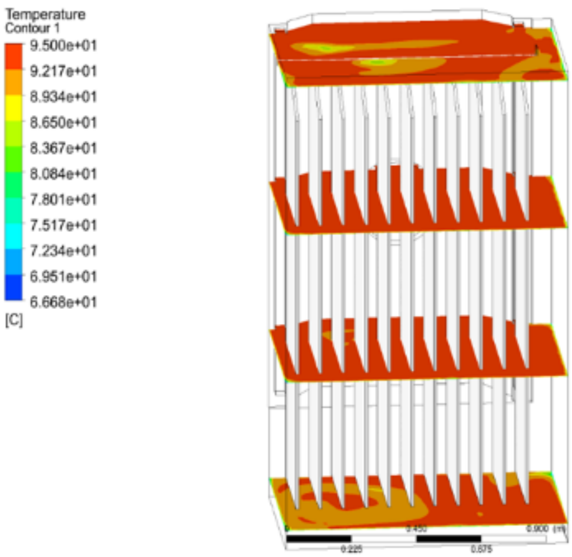

Figure 9. Temperature trend on the set section planes inside the chamber, obtained through the simulation.

More into detail:

- In the upper part of the chamber, temperatures vary between 83 and 95°C (the "coldest" zones are in the middle of the half zone opposite the door, namely on the left of Figure 9);
- Within the two intermediate zones, those deserving more attention for the white coats, temperatures are quite uniform and equal to the set-point value, namely 95°C;
- In the lower part of the chamber, finally, temperature never goes below 89°C; the coldest areas, as it happens in the upper zone, are in proximity of the six white coats farthest from the door (bottom left in Figure 9, orange zones).

According to what has been said, the results obtained at the simulation level can be defined as definitely satisfactory.

3.2. Experimental validation results

According to the simulation results, it was sufficient to monitor the temperature distribution for the validation only at the bottom of the chamber, as anticipated in the methodology section for justifying the positioning of the sensors. Indeed, the upper part is not relevant, since not occupied by the white coats, while in the intermediate volume the distributions were pretty uniform during the simulation. Moreover, since the set-point was at 95°C, it is expected that for lower temperature values, the distributions are more homogeneous in the whole chamber, including *a fortiori* intermediate and upper areas.

At first, a treatment was performed at 95°C under saturated conditions for 1 hour. After this time, all the sensors almost reached the thermal steady state (see Figure 10, where "serie #" refers to the specific numbered sensor). The temperature range reached within the chamber was between 81.8 and 95.3°C (see Table 1 for the detail of the values).

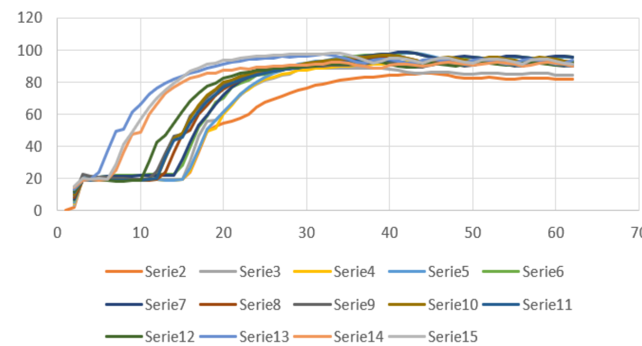

Figure 10. Temperature trend recorded in each of the 14 sensors; the X axis refers to the time [minutes], while the y axis refers to the temperature [°C].

Table 1. Temperature values recorded from each sensor after 1 hour.

# sensor	Temperature [°C]
2	81.8
3	84.4
4	92.9
5	95.3
6	95.3
7	95.3
8	91.5
9	90.4
10	92.4
11	89.9
12	92.1
13	93.3
14	89.9
15	91.1

As expected, the two sensors positioned at the top of the intermediate white coat, i.e. sensors #6 and #7, reached the same temperature value of 95.3 °C, which was the highest recorded in the whole chamber. This demonstrates the initial hypothesis stating that the coldest part is located at the bottom side of the chamber.

As far as the lower zone is concerned, the two sensors closest to the door (i.e. sensors #14 and #15) recorded respectively 89.9 and 91.1°C, so values which can be declared almost similar, while the ones inserted on the second white coat (i.e. sensors #12 and #13) detected 1-2 more degrees; this is in line with the fact that in proximity of the door the heat could be a little bit dissipated.

In the middle of the bottom area, namely where sensors #8, #9, #10 and #11 were inserted, temperatures ranged between 89.9 (sensor #11) and 92.4 (sensor #10); specifically, these two sensors were on the same white coat. It follows that even if being on the same item, the values can vary from side to side, as the difference is of 2.5°C.

Opposite the door, so on the left side of the previous Figure 9, the simulated behavior is confirmed: indeed, here the lowest values of temperature were observed, with a very significant difference between the single sensors. The two sensors opposite the door, i.e. #2 and #3, showed the lowest values of the whole chamber: 81.8 and 84.4°C, which means more than 10°C less than the set-point temperature. A possible and reasonable explanation for this phenomenon can be found in the fact that the simulation takes into account steady state, while data logger, after one hour, was still measuring the increasing chamber temperatures due to the transient conditions. In the penultimate white coat, instead, the situation immediately changed since sensors #4 and #5 returned to values greater than 90°C, namely respectively 92.9 and 95.3°C.

After the first hour, three white coats (and the related sensors), were removed from the chamber, for being subjected to physical tests aiming at verifying whether the treatment has affected the mechanical properties of the material constituting the items or not. This removal was clearly made as quickly as possible in order to not dissipate heat. The white coats in question are the penultimate (with sensors #4 and #5), the intermediate one (with sensors #10 and #11) and finally the one closest to the door (with sensors #14 and #15).

The remaining eight white coats, instead, were subjected to another treatment at the same temperature and humidity conditions, lasting again 1 hour. Table 2 reports the recorded temperature values at the end of this second cycle, i.e. after two hours.

Table 2. Temperature values recorded from each sensor after 2 hours.

# sensor	Temperature [°C]
2	93.6
3	90
4	-
5	-
6	95.2
7	95.5
8	90.8
9	91.6
10	-
11	-
12	92.3
13	93.5
14	-
15	-

As it can be immediately deduced from the table, after two hours the values are closer to the set-point temperature of 95°C. Indeed, the range is between 90.8 and 95.5°C. Temperatures measured by sensors #2 and #3 are now consistent with the CFD simulation.

The two sensors in the upper area, i.e. #6 and #7 did not vary their temperature values, as expectable. Same reasoning for both the situations close to the door and in the intermediate zone, i.e. respectively in presence of sensors #12 and #13 and sensors #8 and #9; the difference in these cases is less than 1°C compared to the 1 hour treatment. The most satisfying result is that after 2 hours, the two sensors which recorded the lowest temperature values after 1 hour (i.e. sensor #2 with its previous 81.1°C and sensor #3 with its 84.4°C), finally both recorded higher temperatures which make them closer to the set-point.

Moreover, again in this case, three white coats were removed for physical tests. Both after 1 hour and after 2 hours, the mechanical properties of the material were brilliantly retained.

In the light of the performed tests, we can immediately deduce that the temperature distributions measured through the fourteen sensors positioned within the chamber were approximately similar to those built thanks to the simulation through the software Ansys. According to that, we can consider the simulation correctly validated, thanks to the tests carried out.

4. Conclusions

This paper aimed at presenting the preliminary results of a project which involves the Department of Engineering and Architecture of the University of Parma and an Italian company producing food machinery, Nilma S.p.A. The ultimate purpose of the project is to convert a food oven into a thermal sanitizer for PPE in response to the numerous shortages and problems originated by the high demand of equipment due do the current pandemic. Moreover, COVID-19 virus is temperature sensitive, and studies on its behaviour under these conditions are still lacking, due to the novelty of the topic.

At the present stage, the machinery was built, and the simulation of the temperature distribution inside the chamber at a set-point of 95°C was performed thanks to the software Ansys, whose outcomes are presented in this manuscript, followed by the experimental validation, successfully performed in May 2021.

Physical tests on the material constituting the PPE were carried out as well, but not presented in this paper as they were beyond the specific scope. However, they showed that mechanical properties of white coats were not affected from a thermal treatment with a very high temperature (95°C for maximum 2 hours), thus maintaining their own safety characteristics.

Regarding the final (and crucial to the success of the project) microbiological experiments with bovine SARS-CoV-2, they are scheduled for June 2021.

More in general, the proposed solution may be useful in response to the problems highlighted in the introduction thanks to different benefits achievable: more possible reuses of a single PPE; less demand; less waste; and also, after an initial economic investment, less purchasing of new PPE.

With regard to this last aspect, in case of positive results from the microbiological experiments, an economic evaluation of the solution will follow, for assessing the real feasibility of the investment.

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