The Virtual PaintShop – Simulation of Oven Curing

Tomas Johnson, Andreas Mark, Niklas Sandgren, Simon Sandgren, Lars Erhardsson and Fredrik Edelvik

Abstract The modeling and simulation of oven curing in automotive paintshops is very challenging including multiple scales, turbulent air flows, thin boundary layers, large temperature gradients and long curing times. A direct brute force conjugate heat transfer simulation of an oven resolving all time and length scales would be enormously time and resource consuming. It is therefore clear that mathematical modeling must be performed, including separation of scales, and a simplification of the heat transfer coupling. We present a novel approach developed in a research project together with the Swedish automotive industry, which makes it possible to accurately simulate a curing oven with close to real time performance. The simulation results are demonstrated to be in close agreement with measurements from automotive production.

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1 Introduction

There is a great need to improve the product preparation process in automotive paintshops to meet future demands on fast adaption and tailored solutions for new material combinations and products. The possibility to perform systematic simulations is then essential and would contribute to sustainable production by reducing the number of prototypes that needs to be painted, and by making it possible to optimize the processes with respect to quality, cost and environmental impact. In earlier work we have presented novel tools for simulation of the spray and sealing processes [3, 4, 6]. The modeling and simulation of the convective ovens typically used in the automotive paintshops to cure the different paint layers is also challenging including multiple scales, turbulent air flows, thin boundary layers, large temperature gradients, and long curing times. A brute force conjugate heat transfer simulation of an oven resolving all time and length scales would be enormously time and resource consuming. Therefore, mathematical modeling is needed to obtain realistic simulations times.

We present a novel approach developed in a research project together with the Swedish automotive industry, which makes it possible to accurately simulate a curing oven in almost real time. The goal is to successfully predict the time dependent object temperature to decrease the number of physical tests that need to be carried out, especially during the production preparation phase. It also allows the oven operator to investigate possible alternative settings of the oven, e.g. flow rates and temperatures. In the approach, the individual nozzles in an oven are simulated to estimate the local nozzle Nusselt number. The Nusselt number is a dimensionless number describing the strength of heat transfer. For a complete oven, the Nusselt numbers of each nozzle are combined to model the effect of the air flow on the solid object, and thereby model the heating. Furthermore, we utilize the novel geometric routines in IBOFlow that efficiently and robustly compute the intersection between a triangular volume mesh and a hexahedral Cartesian mesh [10]. This allows us to accurately describe the solid geometry on a coarse background grid and enables the efficient solution of the heating of objects inside the oven. The novel algorithm and separation of scales approach allow us to simulate on a standard workstation. This is in contrast with previous work on simulation of oven-curing [2], where a Lattice Boltzmann solver in the fluid is coupled with a finite difference solver in the solid, which requires a large cluster to run. The simulation results are demonstrated to be in close agreement with measurements from automotive production, and they can also be utilized for multicriteria optimization [9].

2 Numerical Method

The proposed numerical method is motivated by the fact that a complete time and scale resolved simulation using the Reynolds' averaged Navier-Stokes equation together with conjugated heat transfer is very computationally demanding [2]. This

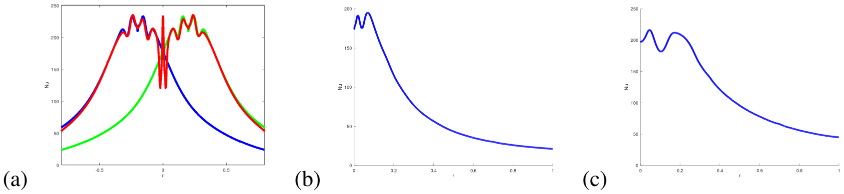

Fig. 1 Nusselt number profiles (a) Comparison between one nozzle and two nozzles profiles (b) $7\,cm$ nozzle profile (c) $10\,cm$ nozzle profile

is especially true since our goal is to present a method where an entire curing process, up to one hour, can be simulated over night on a standard workstation. In this section we will describe how we solve this problem by separating the scales while preserving a physics-based approach, localize the resolved simulations, and couple the localized simulations to the full oven scale.

The numerical method has been implemented in the in-house multi-physics solver IBOFlow® [5], extending earlier available software modules employed in the Virtual Paintshop. The fluid dynamics engine in IBOFlow is a co-located, segregated, incompressible Navier-Stokes solver on an octree based Cartesian mesh, which uses the SIMPLE-C method for pressure-velocity coupling. All geometries are handled with help of an immersed boundary method, for further details see [1, 5, 7, 9].

Turbulence modeling In [13] a comparison between the applicability of different turbulence models to estimate the Nusselt number for impingement heat transfer is performed. The recommendation is to use either Menter's $k-\omega$ SST or Durbin's $v^2 f$ method. We use the SST turbulence model [8], which has lower computational cost and still captures the location of the secondary peak well. The secondary peak can be seen in Figure 1(b-c) and is a typical characteristic of the Nusselt number below a round jet [11, 12, 13]. The heat flux at the solid fluid interface is computed from the friction temperature and velocity. The approach is similar to the one in [11, 12].

Separation of scales Our approach is based on separation and localization. We localize the simulations to individual nozzles to allow us to separate the boundary layer scale from the oven scale. The scale separation contains three steps: motivation, local description, and local to global coupling.

To motivate the approach we study the interference of two nozzles. As can be seen in Figure 1(a) the Nusselt number profile under two nozzles is similar to the duplication of single nozzle profiles. For the local description we generate Nusselt number profiles for a range of diameters and distances, and store all the results for varying diameters and distances in a database. Two such profiles for $7\,cm$ and $10\,cm$ nozzles are shown in Figure 1(b-c). The local to global coupling is performed by projecting the local profiles onto the object.

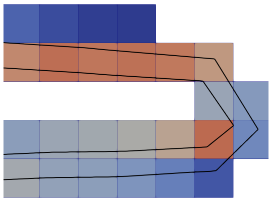

Fig. 2 Discretization of a double sheet metal part on the Cartesian mesh. The mesh is colored by the volume fraction. The conductive heat transfer is solved on the Cartesian background mesh.

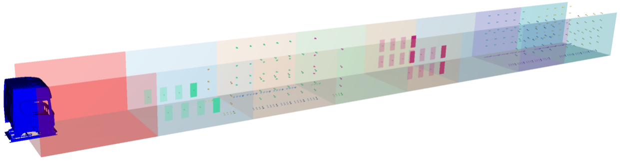

Fig. 3 The discretized oven, where the elevators are modeled as horizontal zones and the cooling zone is split into two zones due to different temperatures. The total number of discretized zones is 8 with a total of 306 circular and 24 rectangular nozzles.

Conductive heat transfer The body of a car or truck cab consists, to a large extent, of $1-2\,mm$ thick sheet metal. In order to resolve such a geometry on a Cartesian grid we use the volume fraction method developed in [10], which allows us to describe the volume and area fractions locally. The method only needs a surface mesh of the object. In Figure 2 an example of an object with two sheet metal parts is shown together with the Cartesian mesh and the volume fractions representing the object.

3 Results

To validate our approach we simulate the curing of a Scania R20H cab in a convective curing oven at the paint shop in Oskarshamn, Sweden. The oven is shown in Figure 3. It has 306 circular and 24 rectangular nozzles. The measurements are performed on a dry cab with 7 probes attached to it. The probes are positioned to give an accurate description of the heating of the cab, including areas such as beams with thicker material. To ensure proper curing the resulting oven curves should match the specification of the paint manufacturer. In particular the minimum time above paint specific critical temperatures must be ensured.

Validation The results of the simulation compared with the measurements are shown in Figure 4. As seen in the Figure the simulations closely capture the temperature profiles from the measurements. The point-wise mean deviation between measured and simulated temperatures for the 7 probes are shown in Table 1. The least accurate probe (2) is positioned on a thin part in the front of the cab, where

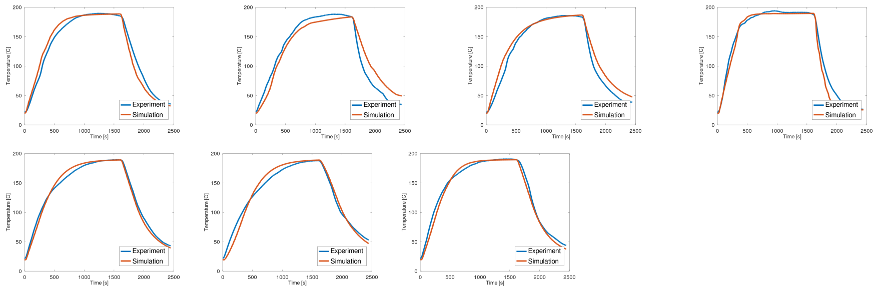

Fig. 4 Validation of the heating of the cab in the oven for 7 probes. They are shown in order from Probe 1 to Probe 7.

position is important, and the projected fluxes give a larger error compared to a full simulation.

Probe	1	2	3	4	5	6	7
Deviation [%]	4.2	7.2	5.0	3.5	2.5	3.6	2.8

Table 1 The point-wise mean deviation between measured and simulation temperatures for the 7 probes.

4 Conclusions

In this paper a novel framework for simulation of convective curing ovens is presented. A validation is performed for a truck cab cured in an oven at the Scania plant in Oskarshamn. Overall the agreement between simulations and measurements is very good, almost within the measurement uncertainty. The conclusion from this and other performed case studies is therefore that the simulations can be used to predict the outcome of the process, optimize process parameters and detect areas with insufficient curing. The framework is integrated in the IPS software (www.industrialpathsolutions.com) as an oven simulation module, complementing the other virtual paintshop tools. The very efficient implementation gives a major improvement of computational speed compared to earlier approaches and makes it possible to perform detailed simulations in close to real time on a standard computer. To simulate an IR oven, that are commonly used in repair shops, would be a simple extension of the work presented here.

The standard tests carried out by the automotive manufacturers are on dry objects. This is consistent with the recommendations from the paint manufacturers. Our initial goal has therefore been to validate such tests as demonstrated in this paper. The natural next step is to include transient tracking of the paint layer thickness and solvent concentration, to allow simulations of the curing itself. Future work also includes to analyze the effect of the oven curing on the adhesive joints from hemming processes.

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