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Simulation of Automotive Paint Curing Process in an Oven

As car makers strive to make vehicle bodies stronger and lighter to meet new U.S. vehicle crash and higher fuel economy standards, they are also facing another tough challenge from their paint shops: adding more reinforcement parts and using foam inserts, special adhesives, and vibration damping materials to improve the vehicle body design. The problem is, those heavy mass and high-heat capacity materials also make the paint curing more difficult. Before a new vehicle model is released, almost every carmaker has the same concerns about whether the paint can be cured properly within the existing or new paint bake ovens, and how the existing oven can be modified to meet the paint cure requirement.

Addressing those concerns requires a method to accurately predict the vehicle body temperature in a vehicle bake oven. Dürr Systems, a worldwide leading supplier of paint finishing systems, uses the Computational Fluid Dynamics (CFD) simulation technique to fully model the vehicle bake oven. After several years of development, Dürr has been able to provide a complete baking simulation on a real vehicle with reasonably good accuracy.

How it works: The computer oven simulation is performed through commercial CFD software, ANSYS FLUENT and self-developed user define function (UDF) codes. The CFD simulation not only can retrieve the temperature-time curve at any point of a vehicle body for paint curing evaluation, but it can also provide a visible digital airflow and temperature field in the oven for engineers to improve their designs before fabrication. Compared with the laboratory oven testing, CFD simulation does not need a real oven and vehicle prototype—it can be performed at the early design stage of the vehicle. This gives car makers a chance to refine the new body design for manufacture, providing more time to modify the existing oven before a new vehicle model release.

CURING REQUIREMENT AND PROCESS

Curing a paint film itself is simple. A basic requirement is to heat up a wet paint film and maintain its temperature for a defined period of time based on a given paint cure window. However, when this wet paint film is on the vehicle body surfaces, meeting this requirement becomes more difficult because the paint temperature is determined by the temperature of the vehicle parts. Curing the paint film on a vehicle body actually turns out to be baking the whole vehicle body. Any parts falling out of the cure window will negatively affect the paint quality in term of appearance or physical properties of the coating. Therefore, an even heat-up of a vehicle body in the oven is a goal of the baking process.

In addition to the paint curing requirement, use of new coating technology (such as 3 wet layer coating) and different body materials also requires a uniform and slow heat-up to avoid potential thermal expansion problems and paint curing issues on the high-heat capacity materials.

Vehicle paint curing happens in a tunnel-like bake oven, where vehicle bodies are heated by high-temperature air. The bake oven typically has three segments: heat-up zones, hold zones and cooling zones. The goals of those segments, respectively, are to heat-up the vehicle to the curing temperature, hold the vehicle body temperature, and cool down the body after the curing process is over. Due to the fact that vehicle bodies move at a constant speed in the oven, accomplishing those goals in each segment is very important and requires a good timing, especially for the heat-up zones. Usually, a key check point for paint cure evaluation is whether an oven can bring all vehicle parts into the targeted curing temperature range at the end of heat-up zones.

SIMULATION CHALLENGES

The vehicle baking process is a three-dimensional, transient conjugate heat transfer process with a relative movement between the vehicle body and the oven. Simulation of this process needs to overcome several difficulties. First, an extremely wide-ranging dimensional scale in an oven has to be accommodated in the model. Ovens are typically several hundred meters long, and the air nozzle or some vehicle parts would be as small as a few inches. Second, many details of the vehicle parts have to be kept for temperature computing. This is because the metal temperature depends on the vehicle part's mass, shape, and connection to others. Keeping those details may result in a big increase in the number of elements in the model. This makes the body clean-up and simplification very tricky and time-consuming. Third, at the curing process, the vehicle bodies are driven by conveyor chain into the oven, one after another. It is impractical to simulate a queue of vehicle bodies in the whole oven. Finally, the radiation heat transfer between the oven wall and vehicle bodies must be considered, whether or not there is a radiation zone. Solving the radiation model requires intensive computing resources.

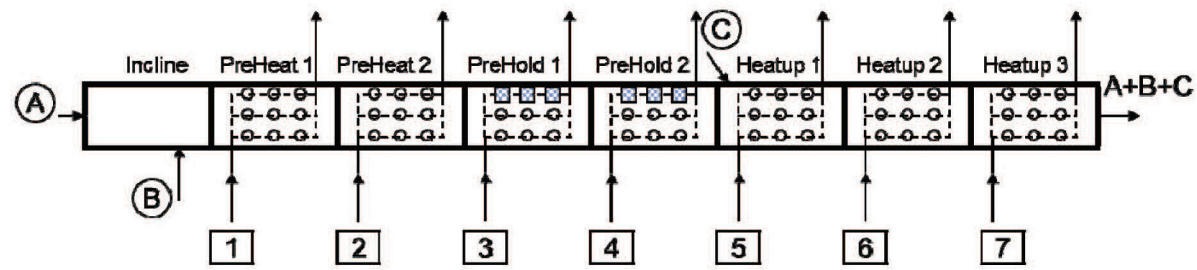

Figure 1. Preliminary oven design and operating conditions used in the simulation.

	Incline Silhouette	Incline Filters	PreHeat 1	PreHeat 2	PreHold 1	PreHold 2	Air Seal	Heatup 1	Heatup 2	Heatup 3
Air Supply Location	A	B	1	2	3	4	C	5	6	7
Air Temp, F	80	338	248	248	248	248	338	357	383	410
Air Volume, acfm	800	5,000	30,000	30,000	30,000	30,000	4,140	30,000	30,000	30,000
Zone Length, m	7		24	21	30	25	5	21	18	22

To overcome those technical difficulties, Dürr has developed a series of approaches on the oven and vehicle body geometry simplification, meshing parameters settings, solving strategy and model set-up. Those approaches, combined with self-developed UDFs, allow the simulation to be more practical and achieve good simulation accuracy.

CFD MODELS

A major assumption of oven simulation is to ignore the wet paint film on the vehicle body, because the film is very thin. The simulation with a body in-white significantly simplifies the physical models of this curing process, although a vehicle body with wet paint can be simulated as well.

An example of an oven simulation project is on a new electro-coat (e-coat) oven that was subsequently fabricated and installed by Dürr. The oven is a convection model consisting of one incline zone, two pre-heat zones, two pre-hold zones, three heat-up zones, three hold zones and three cooling zones (or "cooler"). The total oven length is 325.6 meters and the vehicle conveyor speed is 0.096 m/s.

In this project, the OEM was interested in both heating and cooling processes. The cooling process has two stages: a force convection cooling in the cooling zones and a natural convection cooling in the paint shop building. The latter happens when the vehicle moves from the cooler exit to the tool removal deck. The OEM had a concern about whether the body temperature would be low enough by the time the body reaches the jig removal deck. For this purpose, the simulation is divided into two models: heating model and cooling model. The heating model contains the first seven zones with 30.5 minutes of heating time, and the cooling model starts from the first cooling zone and ends at the jig removal deck. The cooling time is 13.9 minutes in the cooling zones with additional 14.55 minutes in the building. The three hold zones were not modeled in this project because it is relatively easy to maintain the temperature on a vehicle body after it is heated to the desired temperature. The customer had no doubt about the performance of the hold zones.

Given the fact that this simulation started at the early stage of oven design, the simulation is based on a preliminary engineering design and design operating conditions. The simulated oven heat-up zones information and the operating conditions are given in Figure 1.

Creation of an oven simulation generally consists of oven geometry generation, vehicle geometry clean-up, computational domain meshing, and model set-up. For the model's pre-processing, an ANSYS product, ICEM-CFD, was used to create and edit the geometry and mesh the computational domain. After the vehicle body clean-up, about 98% of the original parts were kept in the model, and more than 300 new parts were