Chemical Engineering and Processing 50 (2011) 495–502

Contents lists available at ScienceDirect

Chemical Engineering and Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Investigations of the drying process of a water based paint film for automotive applications

J. Domnick[a,*], D. Gruseck[a], K. Pulli[b], A. Scheibe[a], Q. Ye[b,*], F. Brinckmann[c,*]

[a] University of Applied Sciences Esslingen, D-73728 Esslingen, Germany
[b] Institut für Industrielle Fertigung und Fabrikbetrieb, University Stuttgart, D-70569 Stuttgart, Germany
[c] Institute of Technical Thermodynamics, Technical University Darmstadt, D-64287 Darmstadt, Germany

ARTICLE INFO

Article history:
Received 23 February 2010
Received in revised form 8 August 2010
Accepted 26 August 2010
Available online 2 October 2010

Keywords:
Modelling and numerical simulation
Drying process
Thin film
Water based paint
Automotive application
Paint film defects

ABSTRACT

In a cooperative research project funded by the German BMBF the drying process in the automotive industry has been investigated. More precisely, it was the aim of the project to develop a simulation program that in its final stage allows the calculation of the heat-up process of a fully painted car body, including heat and mass transfer in the thin, water based paint film. The investigations focused on the joint base coat and clear coat drying process used in the automotive industry.

A physical model was developed that treats mass and heat transfer of a ternary mixture applied as a thin film on a substrate. This model was added to the commercial CFD-Solver ANSYS-FLUENT and successfully compared with experimental data in practical conditions. The estimation of paint failures, i.e. pinholes that might occur due to unfavourable drying, which is based upon an empirical model applying a design-of-experiments scheme, was also added to the CFD-Solver.

1. Introduction

It is one of the key efforts in the automotive industry to realize the so-called virtual paint shop. This is basically a complete simulation of the automotive painting process, including the various steps of dip and spray coating as well as drying and curing. Using the virtual paint shop, the painting process of future car bodies may be verified long before extremely expensive full-scale prototypes are available. As part of the virtual paint shop activities, the drying process in the automotive industry has been investigated in a cooperative research project funded by the German BMBF. The project mainly focuses on the physical drying process of water borne base coats prior to curing, which is made together with the subsequent clear coat film. The quality of the final paint film is significantly depending on this base coat drying process, as film defects such as pinholes are related to the process operating parameters.

A typical automotive paint system is shown in Fig. 1f. The water borne base coat is only physically dried (flash-off) before clear coat application. After clear coat application there is a joint final drying and cross linking of base and clear coat at 140 °C. This baking process is important for the final film thickness quality, as various film defects may occur at unfavourable drying conditions, especially at a too fast drying process.

Within this project different stages of experimental and numerical studies have been identified. In general, there are two parts of the investigation. One is the modelling of the unsteady turbulent heat transfer on complex 3D objects; another is the modelling of the evaporating process of a thin film of water born base coat on 3D objects. In previous stages of the research [1–3], investigations of the turbulent heat transfer in various laboratory and industrial dryers have been carried out. Assessments of the available turbulence models used in CFD-Solvers for turbulent heat transfer without paint film were performed, specifically aiming to identify models with low sensitivity of heat transfer prediction on the grid spacing. This is required since considering complex work pieces significant local variations of the grid quality and resolution are expected.

The present contribution presents experimental and numerical results of investigations on the drying process of a thin film applying model water born paint. Drying experiments delivered comparative data for assessment of a paint film drying model that has been implemented into the commercial CFD-Solver FLUENT [6]. The calculated heating-up behaviours on the paint film and the film evaporation rate were compared with experimental results. Furthermore, a model for the occurrence of pinholes as a typical paint film failure related to the parameters of the base coat drying process is introduced.

* Corresponding authors.
E-mail addresses: joachim.domnick@hs-esslingen.de (J. Domnick), qyy@iff.uni-stuttgart.de (Q. Ye), brinckmann@ttd.tu-darmstadt.de (F. Brinckmann).

0255-2701/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.cep.2010.08.021

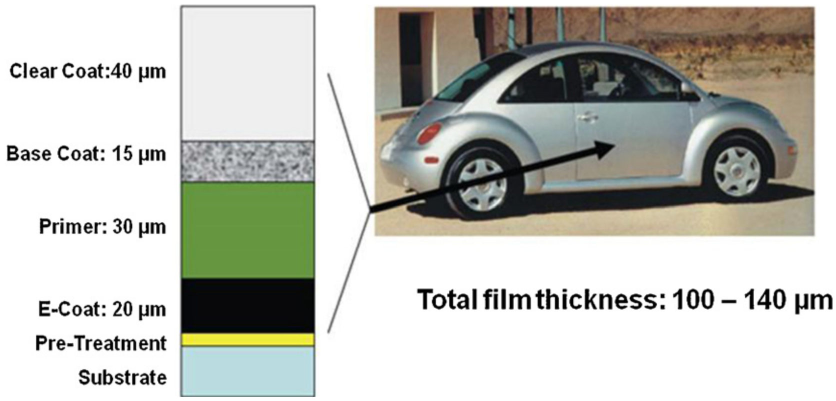

Fig. 1. Typical automotive paint system.

2. Experimental set-up and measuring techniques

The measurements have been performed in a specific oven (Hygrex drying system LBT2500) designed to deliver well controlled air velocity, temperature and humidity. Complying industrial operating conditions, typical water based paint with a solid content of 20% and water and butyl glycol as solvents has been applied on 500 mm × 200 mm large flat panels and further physically dried considering relevant process times. The geometry of the oven and the location of test panel are shown in Fig. 2. Defined horizontal air inlet conditions are produced by individual nozzles in the left wall of the dryer applied with specifically designed flow straightener. This is discussed further below. At the air outlet in the right wall a filter element avoided unwanted influences of subsequent components on the flow field in the dryer.

Local paint film surface temperature using an infrared detector and evaporation rates through weighing were monitored on-line. Furthermore, the water content of the paint film before and after drying has been measured using thermogravimetry. Applying gas chromatography, the fractions of water and additional organic solvents after drying were also detected.

Tests were performed at oven temperatures between 40 and 80 °C, absolute humidities between 6 and 16 g/kg and nozzle inlet velocities between 6 and 20 m/s. These values correspond to conditions used in the automotive industry for forced flash-off of base coats prior to clear coat application. The test panels were painted using either a pneumatic spray gun or an electrostatically supported high-speed rotary bell atomizer with all important spraying parameters being equivalent to the practical application. Applied dry film thicknesses varied between 10 and 25 μm, corresponding to approximately 50 and 125 μm wet film thicknesses before drying.

3. Numerical simulation

The commercial state-of-the-art CFD-Solver FLUENT based on the finite-volume method was applied in the present numerical investigations. A 3D computational domain with typically one million cell elements was created for Hygrex dryer (Fig. 2). Around the substrate plate several boundary layers with prismatic cells were constructed, providing a good resolution of the near wall flow field. Physically, a sufficiently fine grid close to the wall should be employed. As a compromise, an appropriately fine grid with 1 mm as the first interior node distance was used to reduce large computer storage and runtime requirements, especially for later applications using industrial dryers with complete car bodies.

The unsteady Reynolds-averaged Navier–Stokes equations with the *sst-kω* turbulence model that was found [2,3] to give a reasonably accurate prediction of heat transfer with lower grid sensitivity for complicated turbulent flow in drying processes were solved for the gas flow in the dryer. For the heat transfer calculation it was found that the radiation could not be neglected. Here, a discrete ordinates (DO) radiation model was used. The emission coefficient of the electro-coated plate (light grey) and the paint film was taken as 0.95.

For the calculation of the film evaporation, it was found that the traditional approach, which uses Nusselt- and Sherwood-correlations to estimate the heat and mass transfer coefficients in the gas phase, is not suitable for the present drying process due to complicated turbulent flows and three-dimensional substrates. Therefore a novel film evaporation model especially adapted to drying processes in the automotive industry has been developed [4,5] and added as User Defined Function to the CFD-Solver FLUENT [6].

The drying model bases on the mass transport equation due to transient diffusion processes in the direction perpendicular to the

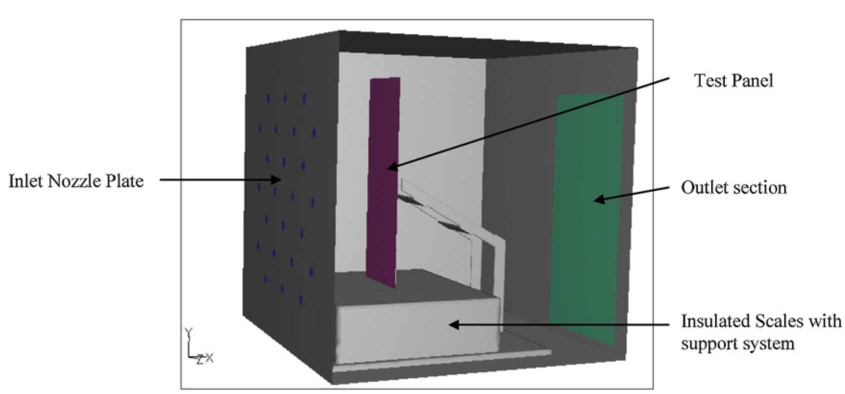

Fig. 2. Test oven arrangement.