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Sensitivity analysis of spray painting process to input parameters: Validation of CFD jet impingement model against an experimental dataset

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ABSTRACT

Accurate modelling of the automotive spray paint process requires using Computational Fluid Dynamic (CFD) simulations built upon a number of interacting physical models. This study examines one component of the air flow in such a simulation – impinging single jet air flow and models the results in a generalizable form to allow comparison with existing practical experiment, validating the results and allowing the development of more complex models based upon reliable results. The results in this paper compare the data produced by four variations of mesh design and wall function using the k–ε model with those produced from previous practical experimental data collected in the European Research Community on Flow (ERCOFTAC) database. The CFD data for each model shows good agreement with the experimental data set in and around the boundary layer close to the jet with particularly good results using the enhanced wall treatment and a fine resolution mesh with a y+(dimensionless wall distance) value of 1. Further refinements are required to fully resolve larger radial distances, however the general results produced show good agreement with expected phenomena.

1. Introduction

This research paper forms part of a larger study and aims to lay foundations for further research on accurately predicting spray paint deposition rate based upon a set of key parameters; the overall goal of the study being to understand the sensitivity of the process to each individual parameter through CFD modelling. This individual paper is intended to study the effectiveness of commercial CFD code at modelling a single jet of air impinging on a surface, creating wall bounded flow (one of the key variables affecting spray paint deposition). By comparing the results from a number of models within the ANSYS Fluent commercial Computational Fluid Dynamics (CFD) package against previous practical results, the validity of the data can be tested and its reliability established for future work: namely establishing the sensitivity of the spray painting process as a whole to its various input parameters.

1.1. Background to automated spray painting

Paint finish quality is of high importance in the automotive industry and across other sectors. Being able to sell high value products requires a consistent, even & blemish free surface with aesthetic appeal, however the quality of a painted coating (and in particular, the thickness of the coating) has other impacts in manufacturing processes, product life cycle and fixed and variable production costs. While it is easy for a casual observer to estimate the impact of an insufficiently thick paint coating (Poor visual appearance, inadequate corrosion resistance), the effects of a thicker than optimum coating are of equal or indeed greater consequence. Visual defects such as paint drips, runs and curtains occur when gravity driven flows pull paint downwards resulting in quality control rejects and rework (and potentially customer dissatisfaction,) while unseen defects can cause problems later in the products life cycle. Industrial drying processes are often calibrated to a particular wet film thickness based on the time taken for the volatiles in the paint to evaporate. When a paint layer is thicker than expected a layer of wet paint will often remain trapped under the surface layer resulting in defects that arise after a product reaches the customer. Insufficiently dry paint also prevents subsequent manufacturing processes from taking place for fear of damaging the wet paint – increasing lead time. Thicker paint coatings also increase variable costs – with an illustrative high solid paint coating having an optimum thickness of around 50 µm – an increase of the same small amount doubles material costs, delays further production and potentially incurs rework or customer returns/dissatisfaction.

Due to the factors listed above, minimizing the variation in spray coating thickness is a major requirement of the automotive industry with automated robot spraying used to provide consistent and precise results. Historically a process of trial and error was used to optimise the

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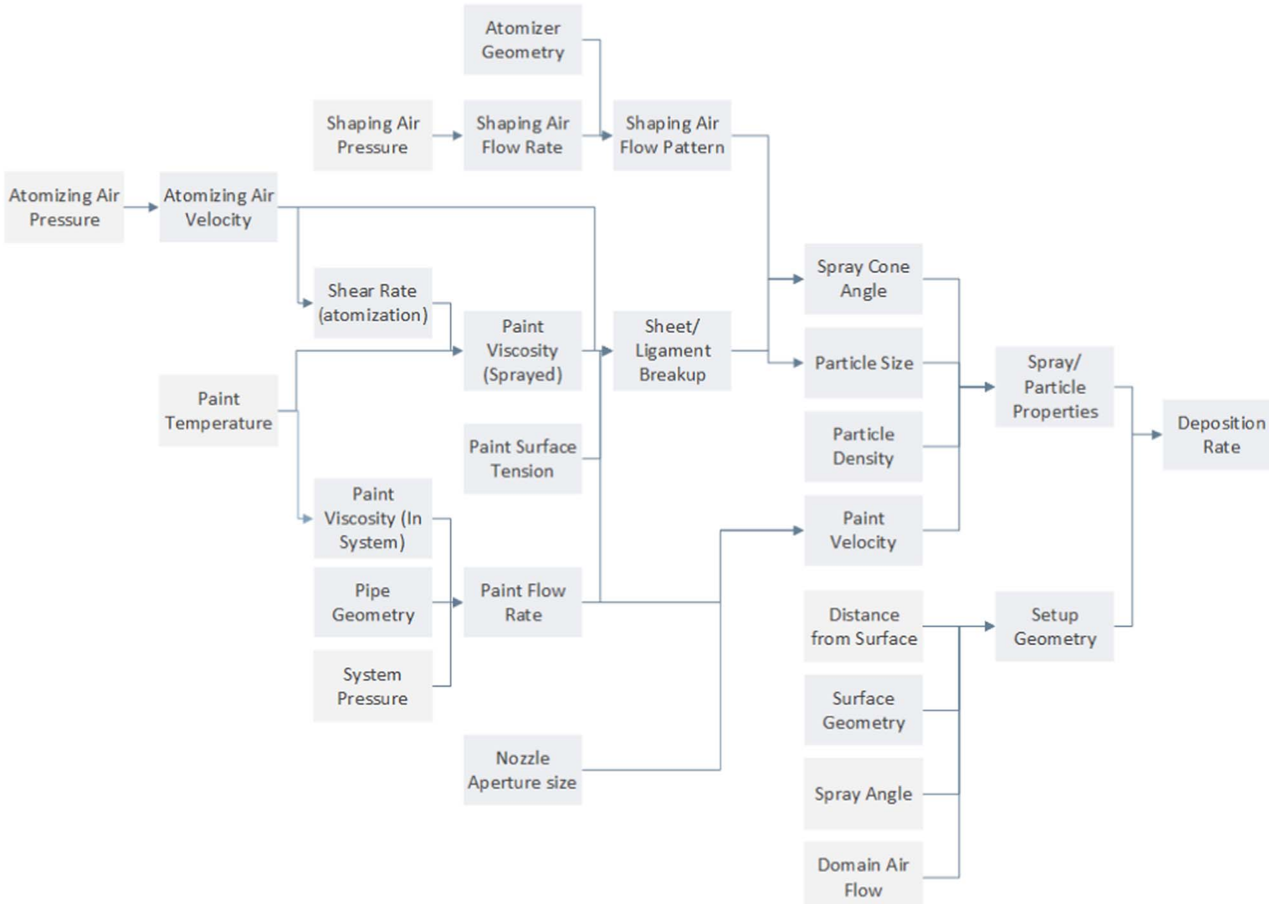

Fig. 1. Map of spray painting variables.

various input parameters (air pressures, distances, viscosities etc.) however CFD modelling has shown an increasing capability for modelling these processes with improving levels of accuracy.

1.2. Simulation of spray paint deposition (general)

Due to the motivations discussed above, significant research into predicting the localised rate of paint deposition in industrial spraying has already been carried out, with several sub-areas of study appearing. Generally speaking, the input parameters responsible for determining paint deposition rate can be mapped as in Fig. 1 [1–7]. Leaving aside the geometry of the set up (which can be easily varied), examining the process below it can be seen that the breakup (and subsequent deposition of paint particles) is dependent on air flow pattern and speed and the rheological properties of the paint and it is these areas that most of the existing literature is focused.

The work of [1,3,5,8] investigate the effect of differing atomizer design (with differing atomisation or breakup mechanisms), while [2–7,9,10] investigate the effect of ambient operating conditions along with paint rheology (although consensus does not appear to have been reached on the effect of paint thixotropy). The research of [11,12] make comprehensive attempts to understand the sensitivity of the whole process to each input parameter; however it remains difficult to properly generalise the results due to the number of variables (and complexity of others such as atomiser geometry).

In almost of all of the current research and industrial application CFD is utilised to effectively model complex flow fields where it would be difficult to obtain experimental result however it is important to ensure the validity of the applied CFD model.

This study focuses on validation of one component of a whole CFD model used to model spray paint deposition. Complete models are comprised of complex continuous and discrete phase models (and the interaction between these two phases) along with assumptions about geometries and rheological properties; however validating these flows with experimental data is problematic. While the study at large hopes to understand the importance that each variable has in affecting the spray painting process, this paper attempts to validate one of the most significant component of the larger model, in this case a single high velocity air jet used to atomize the spray paint impinges on a surface normal to the jet.

1.3. Modelling of jet impingement

When modelling the effect of air flow on deposition rate, the primary consideration is the trajectory of the particles transported within that flow [8,13] – hence the velocity of the flow at a point needs to be measured. While many studies exist relating to CFD simulation of spray deposition, most studies of jet impingement relate to applications in heat transfer (heating & cooling) and aerodynamics (vertical take-off applications) – however many of the studies can be considered to be analogous and used for comparison of outputs. While interested primarily in heat transfer, the works of [14–17] use simulated or experimental setups with appropriate geometries and Reynolds numbers along with measurements of air velocity. In agreement with prescribed practice [18,15] finds that the standard $K–\varepsilon$ model fails to properly resolve the boundary layer turbulence under predicted near wall and over predicting at the outer layer; use of the $k–\varepsilon–\upsilon^2$ model or the newer realizable $k–\varepsilon$ model is recommended.