Investigation of Coating Thickness Sensitivity in Air Knife Coating

P. Tamadonfar (*), A. N. Hrymak (**), J. R. McDermid (*) and F. E. Goodwin (***)

(*) Department of Mechanical Engineering
McMaster University, Hamilton, ON, Canada, L8S 4L7

(**) Department of Chemical and Biochemical Engineering
University of Western Ontario, London, ON, Canada, N6A 5B9

(***) International Zinc Association
1822 East NC Highway 54, Suite 120, Durham, NC, 27713-3210, USA

Presented at the 15th International Coating Science and Technology Symposium,
September 13-15, 2010, St. Paul, MN[1]

INTRODUCTION

The aim of this study is to determine the sensitivity of the predicted coating thickness on a moving sheet substrate in a hot dip galvanizing line due to the effect of different turbulence model assumptions. The numerical results are compared with the experimental data of Lacanette *et al.* [1]. The impinging slot jet is a device which is broadly used in industrial applications in air knives. This device plays a major role in heating of complex surface, cooling of turbine blades, cooling of electronic components, glass sheet tempering, film drying and controlling zinc thickness in the continuous hot dip galvanizing process. A considerable body of previous work exists to model the coating thickness when using a single-impinging slot jet, which used both numerical and experimental methods to gain robust results in predicting the final zinc thickness on the substrate. Thorton and Graff [2] estimated the final film thickness on the substrate ignoring the effect of wall shear stress distributions. Ellen and Tu [3] showed that the coating thickness relies on both the wall pressure and shear stresses on the moving substrate depending on the process conditions. Tu and Wood [4] measured wall pressure and shear stress distributions experimentally for an extensive series of plate-to-nozzle ratios and main jet Reynolds numbers for a single-impinging slot jet. Elsaadawy *et al.* [5] modified the pressure gradient and shear stress distribution correlations using numerical and experimental data. Naphade *et al.* [6] used regression analysis to develop correlations which relate the pressure gradient and shear stress distributions to operating parameters. In a computational study, Naphade *et al.* [6] used the $RNG\ k-\varepsilon$ turbulence model for estimating the coating thickness on the moving substrate, while Elsaadawy *et al.* [5] used the standard $k-\varepsilon$ turbulence model with non-equilibrium wall functions to capture the turbulence quantities in the numerical domains. The coating thickness can be obtained by solving the two-dimensional Navier-Stokes's equation [2-3-5] for the liquid film. In this study the standard $k-\varepsilon$ turbulence model with non-equilibrium and enhanced wall treatments, $RNG\ k-\varepsilon$ turbulence model with enhanced wall functions, $k-\omega$ and shear stress

[1] Unpublished. ISCST shall not be responsible for statements or opinions contained in papers or printed in its publications.

transport (SST) turbulence models are used to approximate the coating thickness on the moving substrate.

NUMERICAL SIMULATIONS

All simulations were solved using FLUENT ™. Figure 1 shows the 2-D configuration of a single-impinging slot jet. In this Figure, z represents the distance between the main slot jet to the substrate, d is the slot gap which is fixed at 1.40 mm and l is the numerical domain length along the substrate direction. For all simulations l/d =100. The wall pressure and shear stress distributions were computed for different z/d ratios, which varied between 2 and 12. The mesh used was comprised of quadrilaterals and was refined for all z/d ratios such that the solution was independent of mesh size. The numbers of nodes varied between 70,000 and 140,000 for different z/d ratios. The 1st order upwind scheme was used for discretization and a double precision solver was used. The velocity inlet conditions were defined for the inlet of the main slot jet and the Reynolds number was based on the inlet velocity and gap width of the nozzle. A channel is added at the jet exit in order to have a fully turbulent flow. The slot jet velocity is about 50 m/s which corresponds to Re =4500. The simulations were run with (5%) turbulence intensity, which is defined as the ratio of the root-mean-square of turbulent velocity fluctuations to the mean flow velocity at the inlet of the nozzles. The turbulent length scale, 7% of the hydraulic diameter, was set to 9.8×10^{-5} for the main slot jet. The substrate was considered fixed because the ratio of the jet velocity to substrate velocity is high and the effect of substrate velocity on wall pressure and shear stress distributions is considered insignificant. The pressure for the far-field boundary condition was set to atmospheric pressure. The non-dimensional wall distance for non-equilibrium wall treatment should lie within log-law region in which $30 \leq y^+ \leq 300$ and inside viscous sub-layer for enhanced wall functions, $k-\omega$ and SST turbulence models where $y^+ \approx 1$.

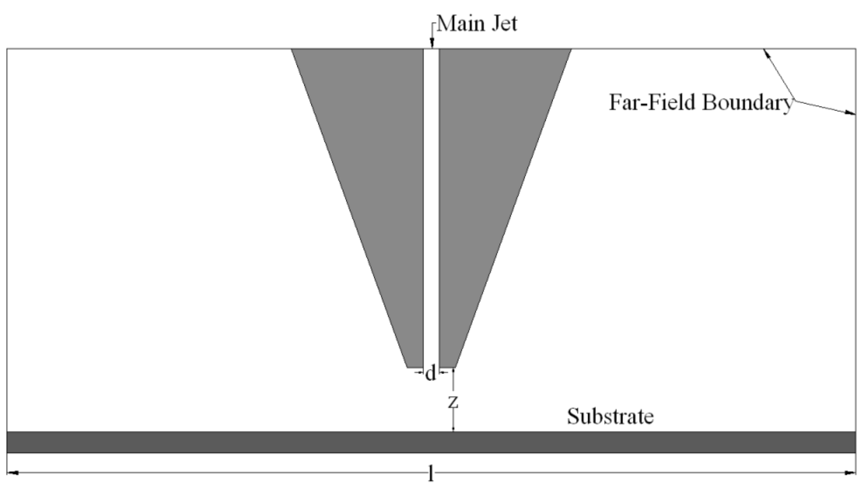

Figure 1: Schematic for a single-impinging slot jet

RESULTS

The turbulence models used in this study have been classified as two-equation models. The above models have two transport equations for turbulent kinetic energy (κ) and the turbulent dissipation rate (ε) or the specific dissipation rate (ω). These models are commonly used in engineering applications and result in lower computational costs in comparison with Durbin's $v^2 - f$ turbulence model [7] and large eddy simulation (LES) method. Figure 2 shows the coating thickness versus z/d ratio based on the wall pressure profile and shear stress results for different turbulence models compared to the experimental data of Lacanette *et al.* [1] for $V_{Substrate}$=1.53 m/s. All of the turbulence models overestimated the coating thickness with respect to the experimental data for z/d ≤8. The range of overestimation for the case of z/d =2 is 30-34%. For z/d =4 and 6, the error values change in the range of 8.2-10.8% while for z/d =8, the error variations are in the range of 2.6-10.5%. The numerical results underestimated the coating thickness for z/d =10 and 12 in comparison with the experimental results. For z/d =10, the standard $k - \varepsilon$ turbulence model with enhanced wall treatment and SST turbulence model have a reasonable correlation with the experimental data. The numerical error changes between 1.2% and 0.4%, respectively. For z/d =12, the SST turbulence model has the best agreement with the experimental results with an error of about 15.3%. The $RNG\ k - \varepsilon$ turbulence model has the highest numerical error for z/d =12 (~34%). It can be concluded that for z/d ≤8, coating thickness is not predicted well by the different turbulence models, and for z/d ≥8 the SST turbulence model has the best agreement with the experimental data.

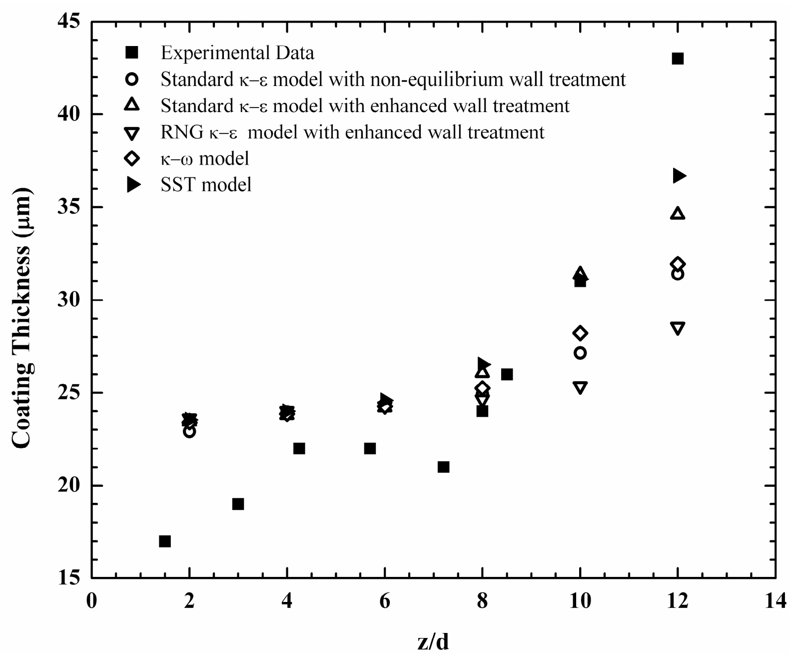

Figure 2: Comparison of the coating thickness of Lacanette *et al.* [1] experimental data with different turbulence models numerical data

Figure 3 demonstrates the coating thickness using the SST turbulence model for different substrate velocities ranging between 0.50 m/s and 2.50 m/s for different z/d ratios. It can be seen for all z/d ratios the coating thickness increases with increasing substrate velocity. By increasing the substrate velocity, the differences between the coating thicknesses of the cases with various z/d ratios are increased. The increments of these differences are more significant for z/d ratios greater than 8.

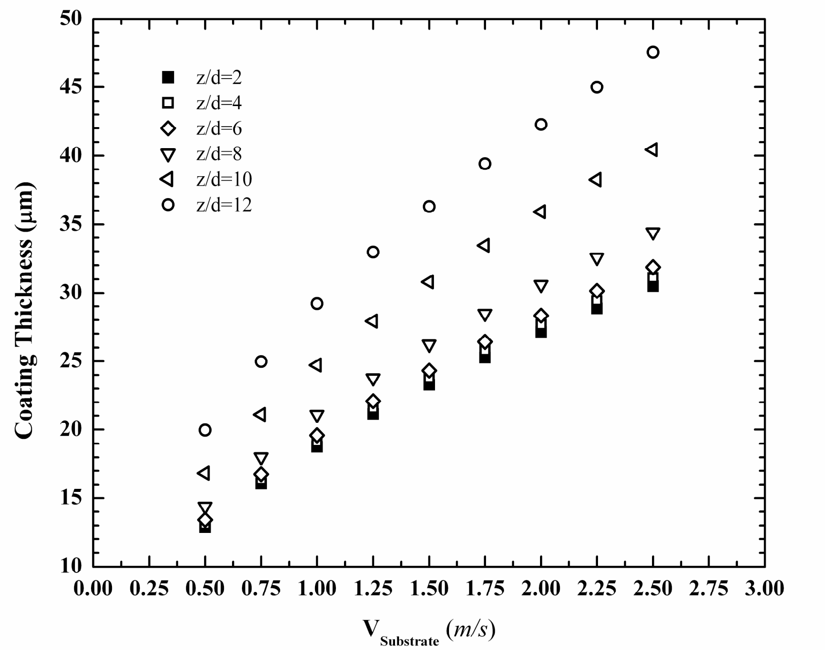

Figure 3: Coating thickness using the SST turbulence model for different substrate velocities for different z/d ratios

REFERENCES

1. D. Lacanette, A. Gosset, S. Vincent, J. Buchlin and E. Arquis, "Macroscopic Analysis of Gas-Jet Wiping: Numerical Simulation and Approach" *Physics of Fluid*, Vol. 18, Issue. 4, Article Number: 042103, 2006
2. J.A. Thorton and H.F. Graff, "Analytical Description of Jet Finishing Process For Hot-Dip Metallic Coatings On Strip," *Metallurgical Transactions B-Process Metallurgy*, Vol. 7, Issue. 4, 1976, pp. 607-618
3. C.H. Ellen and C.V. Tu, "An Analysis of Jet Stripping of Liquid Coatings," *Journal of Fluids Engineering*, Vol. 106, Issue. 4, 1984, pp. 399-404
4. C.V. Tu and D.H Wood, "Wall Pressure and Shear Stress Measurements Beneath an Impinging Jet," *Experimental Thermal and Fluid Science*, Vol. 13, Issue. 4, Nov 1996, pp. 364-373
5. E.A. Elsaadawy, G.S. Hanumanth, A.K.S. Balthazaar, J.R McDermid JR, A.N. Hrymak and J.F. Forbes, "Coating Weight Model for the Continuous Hot-Dip Galvanizing Process," *Metallurgical and Materials Transactions B,* Vol. 38, Issue. 3, June 2007, pp. 413-424
6. P. Naphade, A. Mukhopadhyay and S. Chakrabarti, "Mathematical Modeling of Jet Finishing Process for Hot-Dip Zinc Coatings on Steel Strip," *ISIJ International*, Vol. 45, Issue. 2, 2005, pp. 209-213
7. M. Behnia, S. Pareneix, Y. Shabany and P. A. Durbin, "Numerical Study of Turbulent Heat Transfer in Confined and Unconfined Impinging Jets," *International Journal of Heat and Fluid Flow*, Vol. 20, Issue. 1, 1999, pp. 1-9