Fluid structure interaction (FSI), an important simulation tool

Fluid structure interaction (FSI) is the interaction of static, moving, or deformable structural components with a fluid flow. FSI is one of the most important examples of multi-physics problem solving. FSI has wide-ranging applications, ranging from large-scale problems such as the dynamic instability of a bridge subject to a strong wind, to small-scale problems such as the flow of blood through a heart valve.

When FSI occurs, fluid flow deforms a physical structure. The deformation of the structure in turn changes the fluid flow. Traditional fluid flow simulation does not account for the deformation interaction. Such simulations will at least be incomplete. At worst, they will be misleading and may well not show up a problem which could have catastrophic consequences. Without FSI analysis, the resulting product may not perform as expected, and costly and time-consuming redesigns may be necessary. FSI simulation allows the interactions between fluids and structures to be predicted, enabling engineers to visualise and optimise the behaviour of complex products with the highest confidence. The engineering team can investigate complex engineering problems in depth and gain a much better understanding of their product's behaviour.

The physical theory behind FSI can be very complex. In providing the following example of an FSI analysis, we have selected a simple example where the trend of results could be arrived at intuitively. However, you will see that FSI provides a level of detail unlikely to be matched by any physical experiment. For this sample analysis, we will apply FSI to the blade coating process.

The blade coating process

Blade coating (also known as tape casting, knife coating, or doctor blading) is an established low cost ceramic forming technique for the manufacture of large areas of ceramic tapes and sheets. In the 1940s, blade coating was introduced as a method of producing thin sheets of piezoelectric ceramics and capacitors. Today, the technique is widely used in the production of many different devices, e.g. electronic substrates, multilayer ceramic packages, polymer batteries, photovoltaics, or electrodes for molten carbonate fuel cells. Films as thin as 5 micrometers can be produced using blade coating. A typical blade coater is shown in Figure 1.
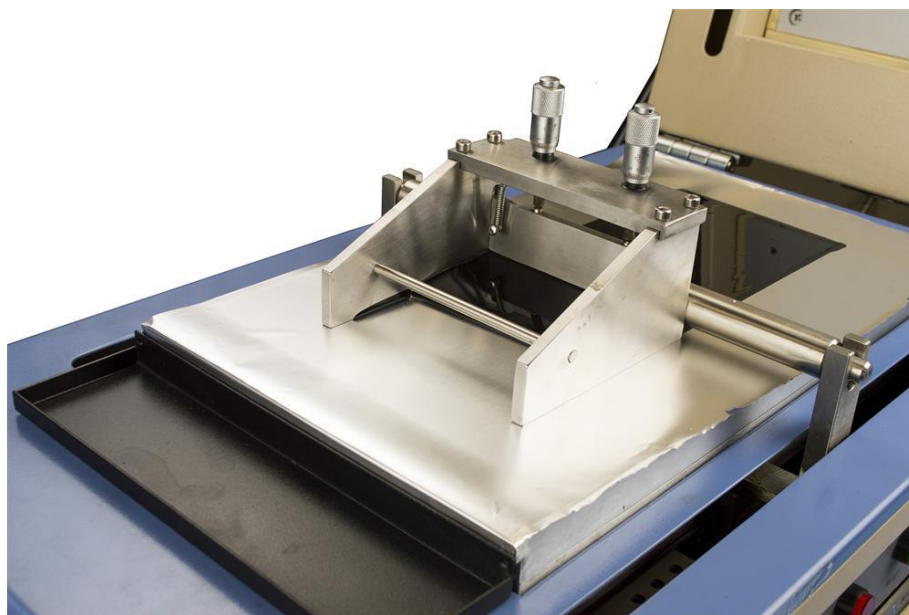

Figure 1: Photograph of blade coating in progress [1].

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In the blade coating process, ceramic slurry is deposited onto a rigid or flexible substrate via a controlled gap under a blade that moves relative to the substrate. In practice, the coating blade may move over the substrate, or the substrate may move under the fixed position blade. The slurry usually consists of a suspension of ceramic particles and other additives such as binders, dispersants, or plasticisers. The surface quality and thickness of the ceramic sheet is determined by a complex interplay of factors, including the slurry properties, the pressure head of the slurry, the gap under the blade, the velocity of the substrate relative to the blade and the surface and mechanical properties of the blade and substrate. After coating, the thin ceramic layer is dried and sintered. Figure 2 is a schematic of a typical blade coating process from the beginning of the powder preparation through to drying.
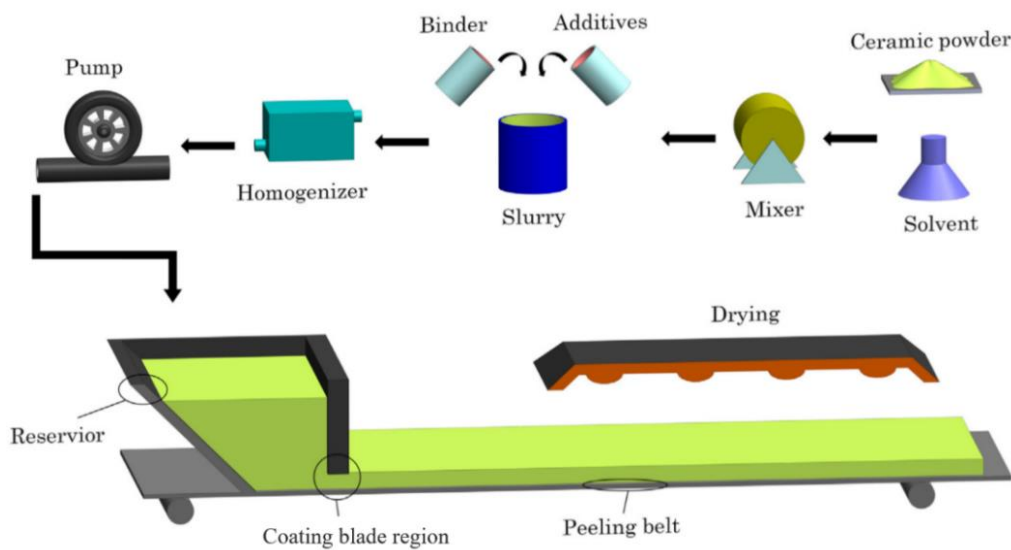

Figure 2: A schematic of blade coating process [2].

Because of the number of influencing factors, the achievement of the desired coating thickness and surface quality can involve extensive trial and error experimentation. In certain cases, as long as the coating fluid is translucent, a Laser Doppler Velocimeter (LDV) as shown in Figure 3 can be used to study the flow field experimentally. The LDV technique is relatively expensive to implement.
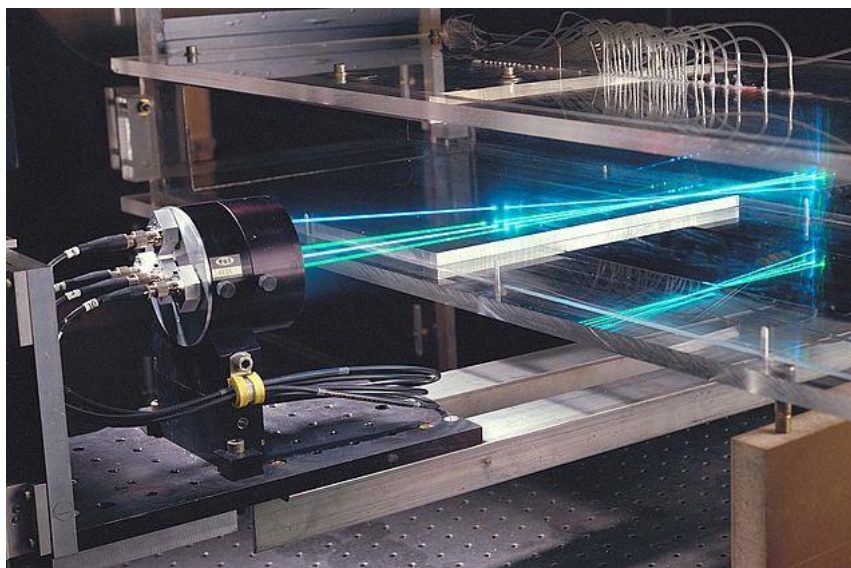

Figure 3: A Laser-Doppler Velocimeter placed at a flow channel.

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In cases where the desired coating thickness and quality is difficult to achieve experimentally, a numerical simulation of the process would clearly be advantageous. Simple numerical models have been used for some years, but these have mostly been limited to two dimensional (2D) studies. As discussed in [4], these earlier models could not predict three dimensional flow effects, nor consider any effects caused by flexing of the blade. The author now contends that 3D modelling is feasible.

Our 3D analysis and modelling of the blade coating process combines Fluid Structure Interaction (FSI) analysis and multi-phased Volume of Fluid (VOF) analysis. Combining the two approaches allows the whole coating process to be simulated in three dimensions. With the animated 3D results, we can study the lateral behaviours of the slurry and the blade, and the quality of thin film along the two sides. Our 3D numerical approach enables complex coating processes to be studied at a level of detail not previously possible.

While a more detailed discussion of the 3D analysis and modelling of the coating process follows, for a quick overview of what can be achieved through numerical modelling please view the animations and better quality diagrams here http://www.caebay.com/animations/.

Example machine configurations analysed

For this example, two typical types of blade coating techniques are analysed. One with a reservoir and one without. For simplicity, we will consider the machine configuration where the substrate is static and the blade/reservoir moves at with constant speed. These configurations are illustrated in Figures 4 and 5. For further simplicity of explanation, we will also assume that the fluid is Newtonian (constant viscosity coefficient), and that other parameters such as the blade gap and blade thickness are constant. In practice, the method can be applied to non-Newtonian, porous, compressible, and power-law fluids and to variable machine configurations and material parameters.
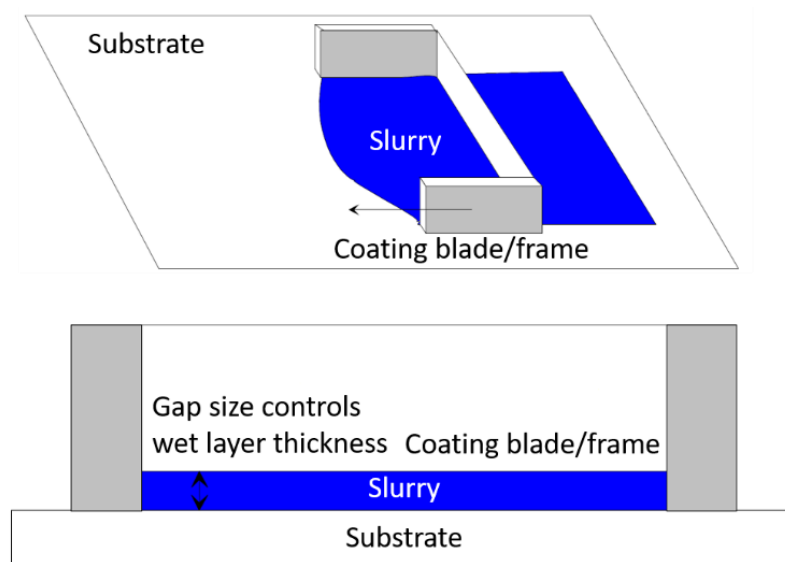

Figure 4: Principle of blade coating using blade/frame only. The frame is moving and coating liquid along the substrate (top image). Wet layer thickness is controlled by the gap between the blade and the substrate (bottom image).

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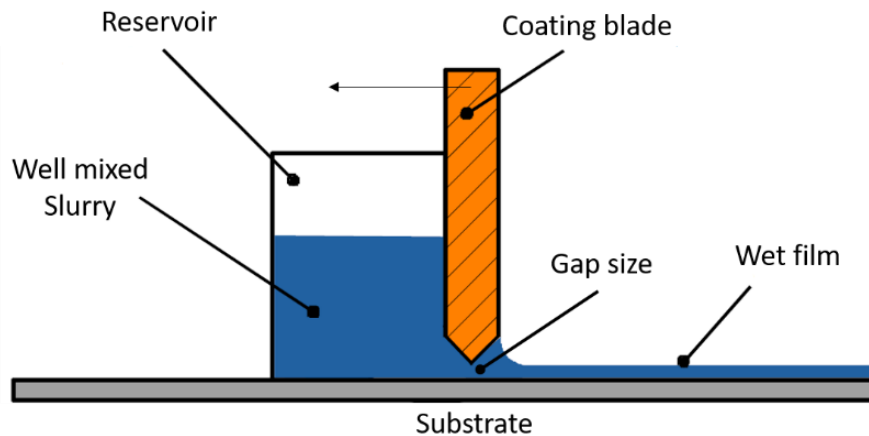Discrete element method | Heat transfer

Figure 5: Principle of blade coating using a reservoir which stores a sufficient amount of slurry. The tank with blade at the front is moving along the substrate to coat a wet film.
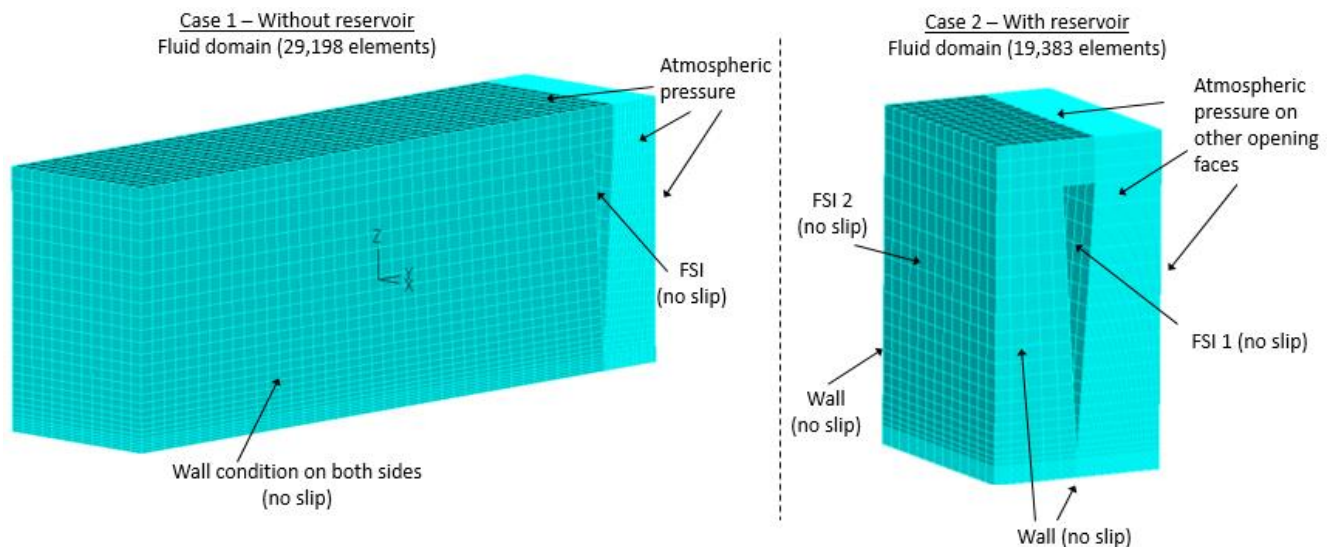
Example material properties

In this analysis, the coating blade is made of standard steel and the CL3000 slurry is chosen. Their respective material properties can be found in Table 1.

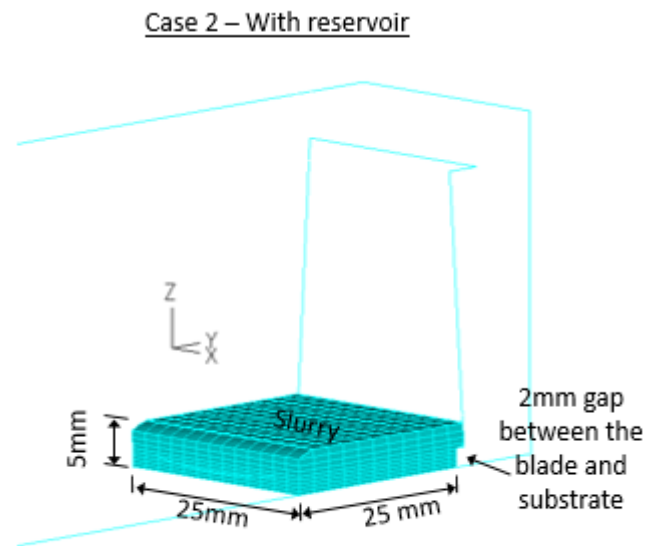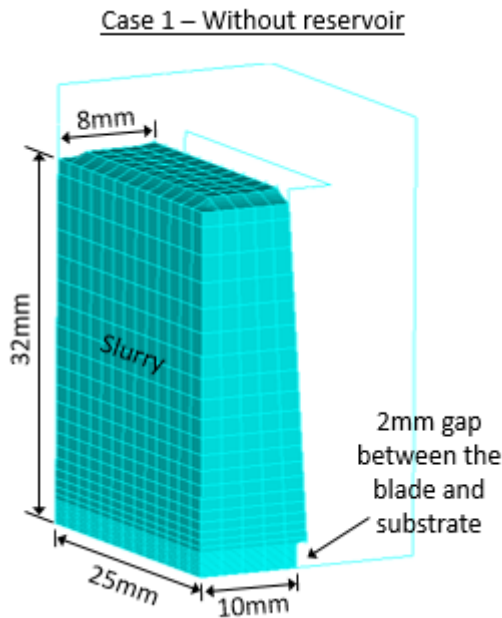Table 1: Material properties of the blade, slurry, and air used in simulations.

Properties	Steel blade	CL3000 slurry	Air
Density (g/mm^3)	7.80×10^{-3}	3.80×10^{-3}	1.02×10^{-6}
Young's modulus (N/mm^2)	2.10×10^{5}	---	---
Poisson ratio	0.30	---	---
Viscosity (N/mm^2-ms)	---	3.15×10^{-3}	1.51×10^{-8}
Coefficient of tension (N/mm)	---	3.55×10^{-5}	0.00
Atmospheric pressure (N/mm^2)	---	---	0.101

Simulation setup

Fluid meshing and boundary conditions (FSI = Fluid Structure Interface)
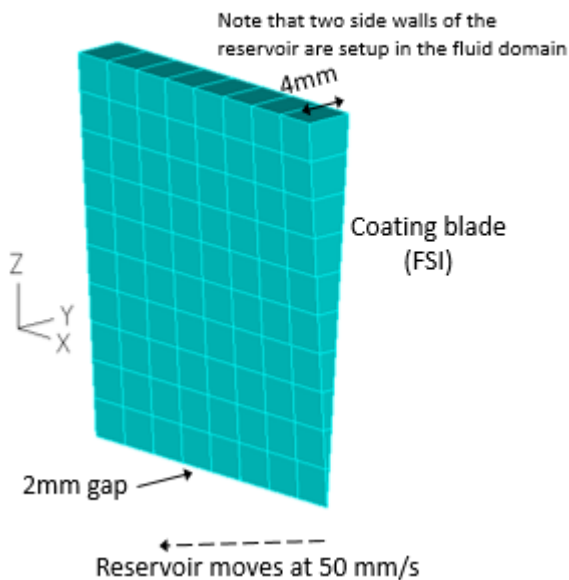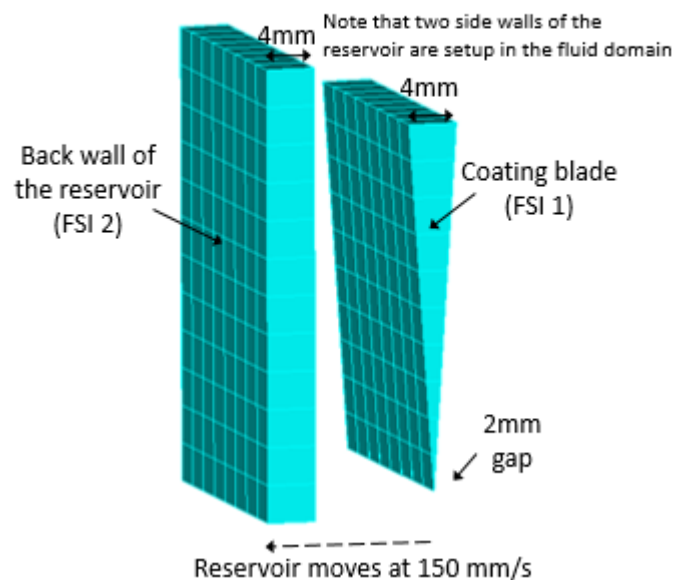
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Initial conditions of slurry

Case 1 – Without reservoir

8mm

32mm

Slurry

25mm

10mm

2mm gap between the blade and substrate

Case 2 – With reservoir

Z
Y
X

Slurry

5mm

25mm

25 mm

2mm gap between the blade and substrate
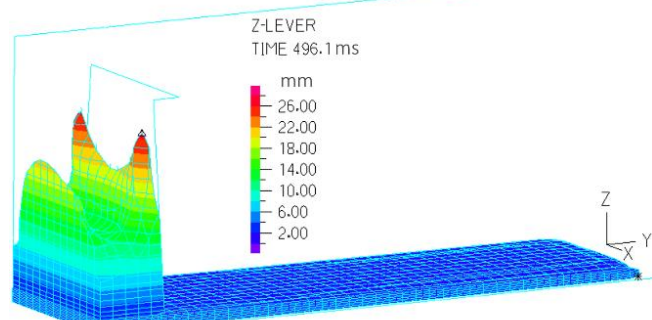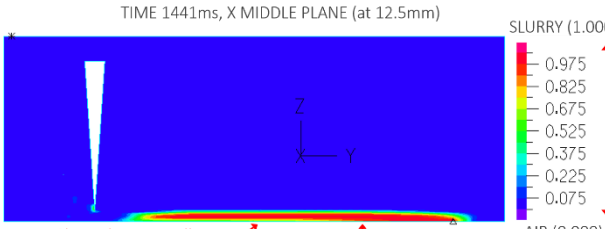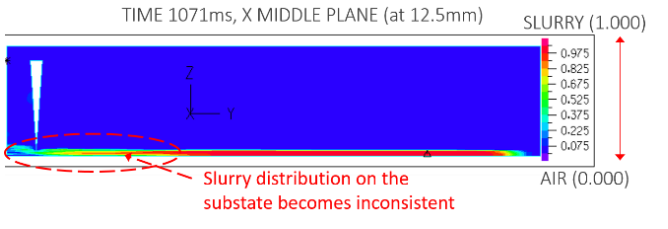
Structure meshing and boundary conditions
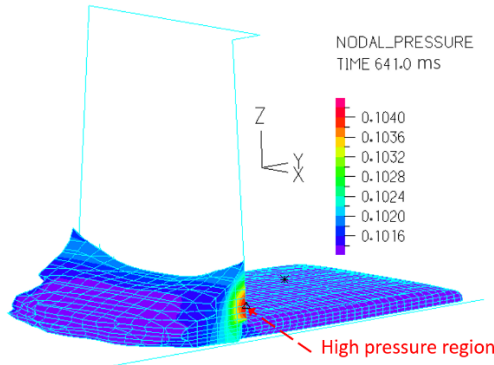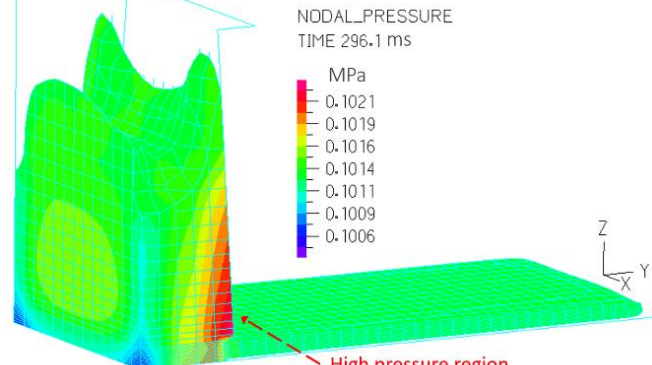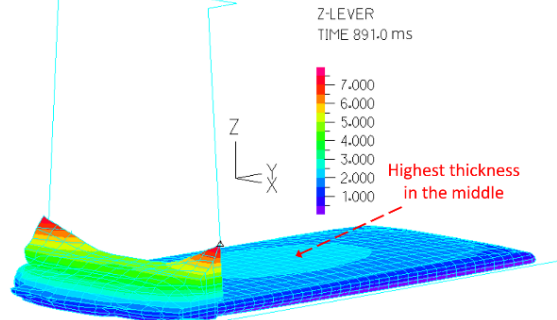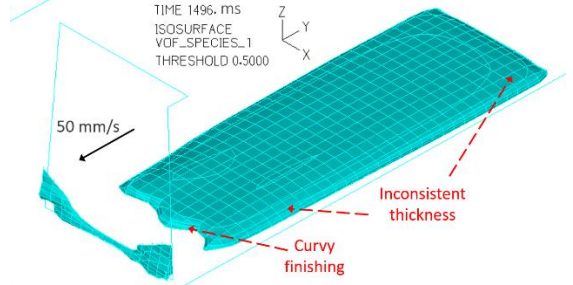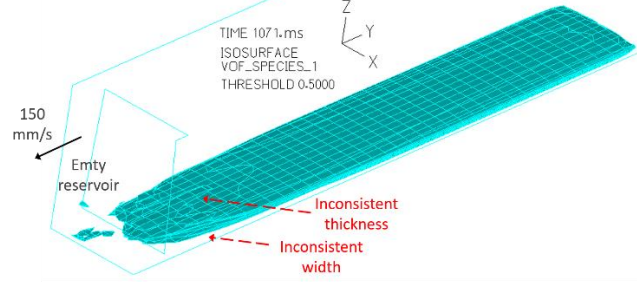
Case 1 – Without reservoir
Structure domain (176 elements)

Note that two side walls of the reservoir are setup in the fluid domain

4mm

Coating blade (FSI)

Z
Y
X

2mm gap

Reservoir moves at 50 mm/s

Case 2 – With reservoir
Structure domain (80 elements)

4mm

Note that two side walls of the reservoir are setup in the fluid domain

4mm

Back wall of the reservoir (FSI 2)

Coating blade (FSI 1)

2mm gap

Reservoir moves at 150 mm/s

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Simulation results and discussions

Case 1 – Without reservoir	Case 2 – With reservoir
Nodal pressure distribution of the slurry	
The difference between the maximum and minimum stresses is not significant.	Although the fluid near the bottom of the blade has higher pressure than that of the rest, the difference is not significant.
Z-level of the slurry	
The wet film's thickness varies across the longitudinal (Y) and lateral (X) axes. Slurry level at the middle is higher than the surrounding edges.	The wet thickness is quite consistent along the substrate when the slurry level in the tank is sufficient.
The slurry does not adhere well onto the substate starting very early in the process.	The slurry distribution becomes inconsistent towards the end of the process when there is insufficient fluid left in the tank
More results show the thickness distribution of the slurry coat	Further results show the thickness and width of the slurry flim are inconsistant at the end of the process.

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Bottom adherence

TIME 1441. ms
ISOSURFACE
VOF_SPECIES_1
THRESHOLD 0.5000

Void

Bottom view

TIME 1071. ms
ISOSURFACE
VOF_SPECIES_1
THRESHOLD 0.5000

Void

Bottom view

Structural stress distribution

SMOOTHED
EFFECTIVE
STRESS
RST CALC
TIME 548.5 ms

0.3900
0.3300
0.2700
0.2100
0.1500
0.0900
0.0300

The slurry creates stress
onto the coating blade

SMOOTHED
EFFECTIVE
STRESS
RST CALC
TIME 598.5 ms

MPa

1.950
1.650
1.350
1.050
0.750
0.450
0.150

The slurry creates stress
onto the coating blade

Comments on simulation results

- Case 2 produces wet layer more consistently than Case 1.

- Case 1 has relatvely larger void at the bottom than that of Case 2.

- Insufficient level of slurry in the reservoir leads to inconsistent slurry distribution, better results can be obtained for Case 2 if the reservoir is being constantly filled up during the process.

In summary, simulation results show the distintive characteristics and outcomes of the two processes. While Case 1 has simplier configurations, the resulting slurry quality is not as good as that of Case 2.

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The benefits of FSI simulations

The example analyses demonstrate that the combination of FSI and VOF techniques delivers both precise and visually illuminating solutions to complex multiphysic and multiphasic problems. Even the most expensive of physical experiments are unlikely to present solutions with similar precision and clarity.

Similar numerical simulations can be used to predict the behaviours of both multiphase and power-law fluid and flexible structures. Detailed results such as stress, displacement, liquid distribution, wall adherence and velocity can be easily visualised and analysed. For coating machine manufacturers, the application of these simulation techniques can reduce machine development costs and development time.

In a similar manner, these techniques can be applied to problem solving in many other areas of applications, of which a few examples follow:
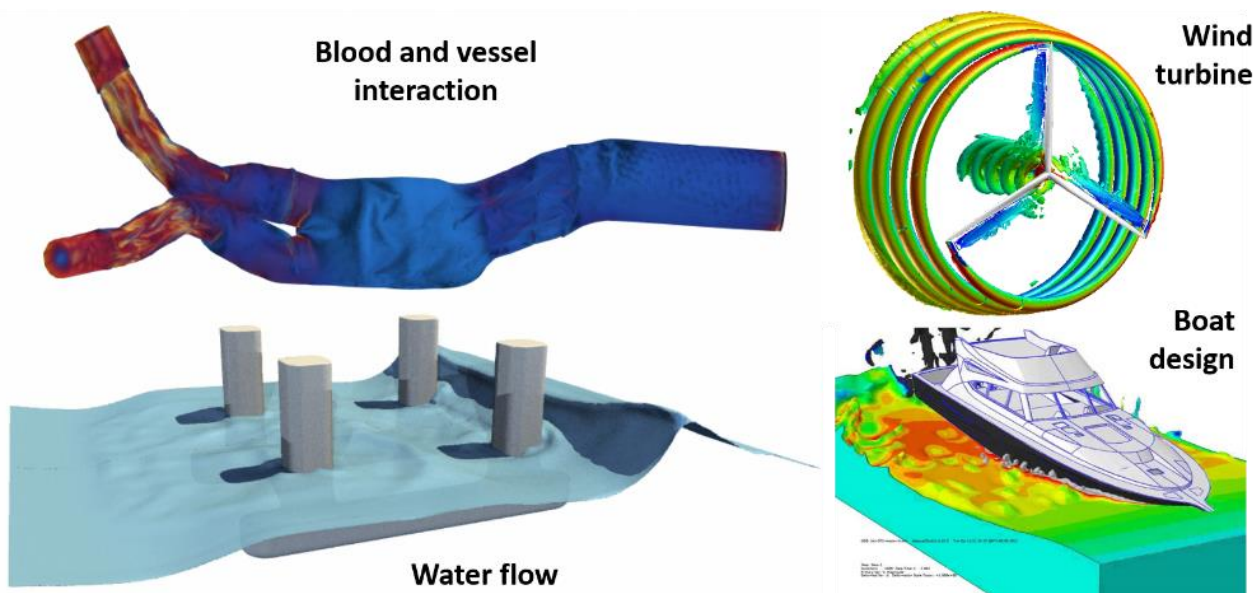
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[1] http://www.mtixtl.com. Accessed on 30 Oct 2017.

[2] Jabbari M., Bulatova R., Tok A.I.Y., Bahl C.R.H., Mitsoulis E., and Hattel J.H. (2016). Ceramic tape casting: A review of current methods and trends with emphasis on rheological behaviour and flow analysis. Materials Science and Engineering B, 212, 39–61.

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[6] Hirt C.W. and Nichols B.D. (1981). Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries. Journal of Computational Physics, 39, 201-225.

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