UBC

Pulp and Paper Applications
Mechanical Engineering CFD Modelling

Dr. Martha Salcudean
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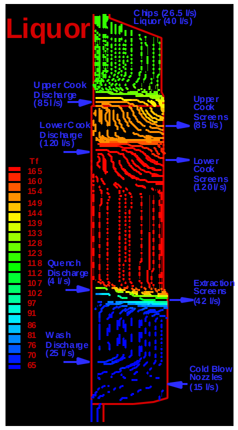
Recovery Boilers | Bark Boilers | Headboxes | Lime Kilns | Wood Kilns | Hydrocyclones | Screens | Digesters | Fractionation

Process Modelling Group



For more than a decade, the UBC Mechanical Engineering industrial process modelling group has been developing numerical models in the pulp and paper industry. We pioneered process modelling in recovery boilers in the early 90's and extended this work to most of the major equipment in the Kraft process. The process models, which have been developed, are tailored to assist mills to resolve complex industrial problems. The models are applied to mills operating capital-intensive equipment in order to reduce costs and eliminate unscheduled down time. The outcome of this effort is to provide detailed analysis and useful recommendations for operational and design changes, to help improve equipment performance and reliability, to provide knowledge that has a significant impact on decision making, and to reduce financial risks in retrofits and the purchase of new equipment.

Modelling Group

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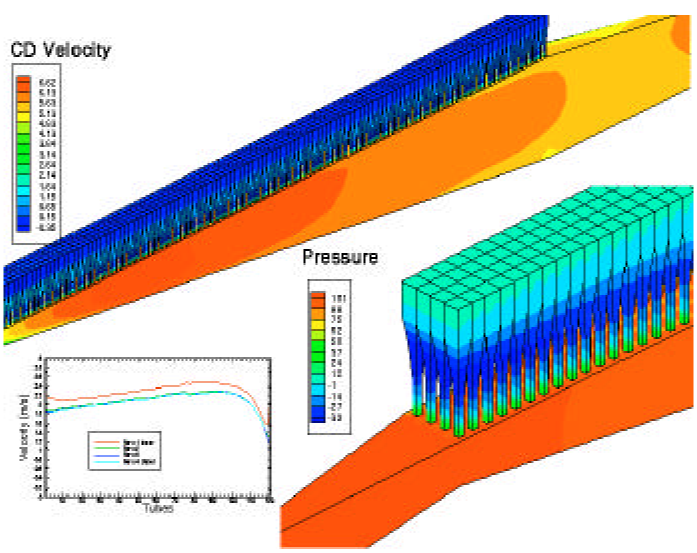
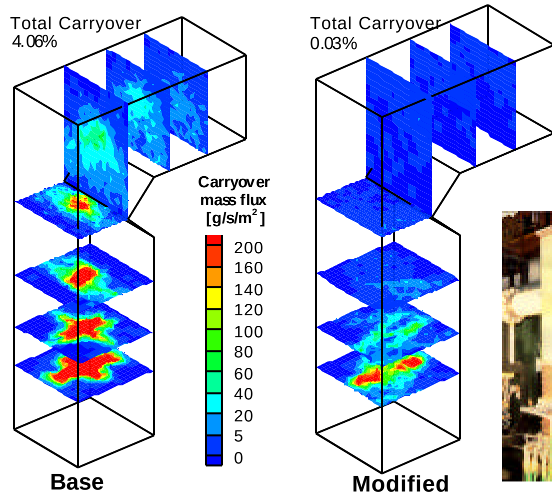
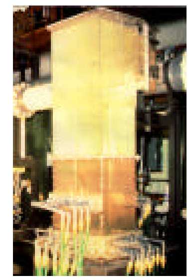
Note: UBC and PSL Personnel (Pulp & Paper Section)







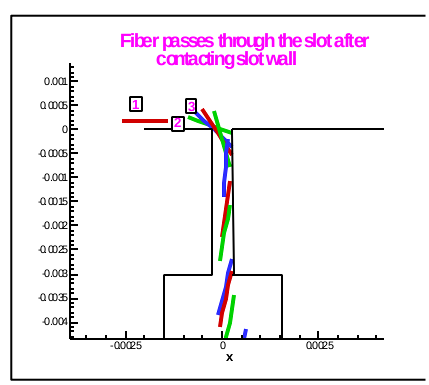
Process Modelling Steps

- Collect physical and operational characteristics
- Build a state of the art in-house numerical model incorporating previous advances in numerical modelling
- Validate models with industrial measurements or with physical models
- Apply the models to industrial processes
- Interpret the results
- Complete parametric studies
- Use the models to evaluate "what if" scenarios to improve operation and design
- Licence the models for industrial application

Areas of Expertise

UBC has worked on developing process models in the following pulp and paper areas:

- **Recovery boilers**
- **Bark boilers**
- **Digesters**
- **Headboxes**
- **Lime kilns**
- **Drying kilns**
- **Hydrocyclones**
- **Screens**
- **Fibre fractionation**



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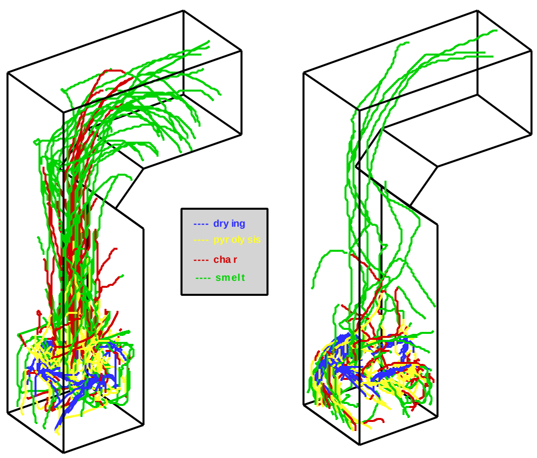
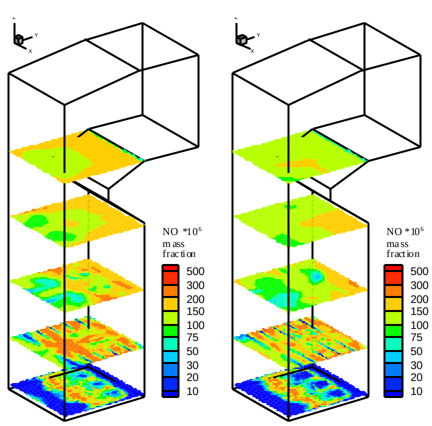
RECOVERY & BARK BOILERS

Boiler designs and modifications have been traditionally based on experience and simple physical modelling. The complex nature of the turbulent gas flow and combustion in boilers limits this type of approach. Operating a boiler above the design load often leads to problems such as excess carryover, high combustion gas emissions, elevated thermal stresses, and fuel bed instabilities.



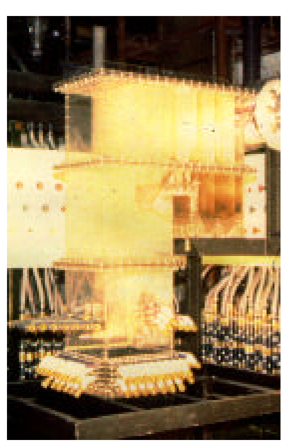
Base   Modified

BOILER MODEL: Over many years the UBC modelling group has developed sophisticated recovery and bark boiler analysis tools that can simulate the complex details of an operating boiler. These tools can be used to predict in advance the outcome of any boiler modification, including combustion air and fuel flow changes, or a complete retrofit of the air and fuel delivery systems. The 3-D computational method models the airflow, jet interactions, turbulence, fuel combustion, and wall and gas radiation. Flow equations are coupled to the energy and species conservation equations. The model predicts gas flows, composition, temperature, and fuel particulate distribution. Simulation results allow for a thorough understanding of the boiler operation, and provide the basis for optimising the existing air and fuel systems. In some cases it may be sufficient to improve the boiler's operating practices; in other cases, it may be beneficial to retrofit the boiler with a new air or fuel delivery system. *Weyerhaeuser* and *PSL* provide funding for the boiler programs.



BASE CASE
UGA 1m/s
OFA 30m/s

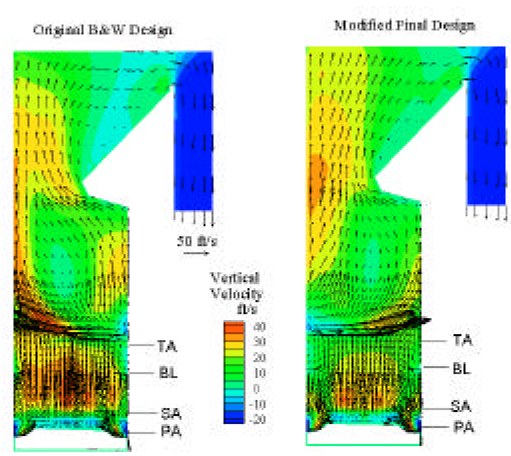
MODIFIED CASE
UGA 0.8m/s
20% of UGA moved to OFA
OFA interlaced, 60m/s:30/s



WHAT MODELLING CAN ADDRESS

- Increase the load and efficiency of the boiler
- Reduce operational costs
- Significantly reduce decision making risks
- Provide valuable information for operator training
- Improve gas mixing and combustion effectiveness
- Lower excess air necessary for complete combustion
- Minimise particulate carryover and unburned char
- Minimise emissions of CO_2, CO, TSR, and NO_X
- Improve overall thermal efficiency
- Optimise firing strategies for different loads/fuels
- Increase the capacity of the boiler
- Improve the stability of the boiler
- Minimise the danger of waterwall tube failure, or floor corrosion
- Analyse and recommend choices of air and fuel system upgrades

MODEL APPLICATION: The model is licensed to Process Simulations Limited (www.psl.bc.ca) which specialises in process modelling in the pulp and paper industry.



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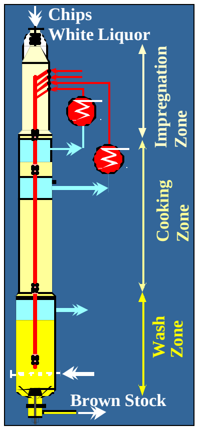
Digesters

Chemical reactions in the digester are mainly controlled by the liquor composition, the chip characteristics, and the liquor flow conditions. A three-dimensional, coupled two-phase computer model of a continuous Kamyr digester has been developed at UBC. The objective of the digester model is to create an effective digester tool to improve performance, yield, and fibre strength, address mill issues, and evaluate planned retrofits ahead of time.



Model Description: Liquid and solid conservation equations of mass, momentum, energy and solid species concentration have been developed from first principles and coupled to simulate the Kraft pulping process. Pulping is modelled by using a wood chip degradation, alkali consumption, and diffusion model through the chip. In addition to the lignin and carbohydrate concentration, the model predicts the velocity, pressure, and temperature distribution throughout the digester for both the liquor and the wood chips. A block-structured curvilinear grid system represents the digester geometry accurately. This model is an improvement over previous 1-D and 2-D models, which ignore convection terms, assume irrotational flow, and do not model interaction between phases. *Canfor* and *NSERC* provide funding for the digester program.

Liquid

$$\frac{D\varepsilon_1\bar{\rho}_s\bar{V}_s}{Dt} = \nabla\cdot\varepsilon_1\bar{\sigma}_s - \frac{1}{U_0}\int_{S_{sf}}\bar{\rho}_s\bar{V}_s(\bar{V}_s-u)\cdot\nu_s\,dS + \frac{1}{U_0}\int_{S_{sf}}\sigma\cdot\nu\,dS + \varepsilon_1\rho_s\bar{F}_s$$

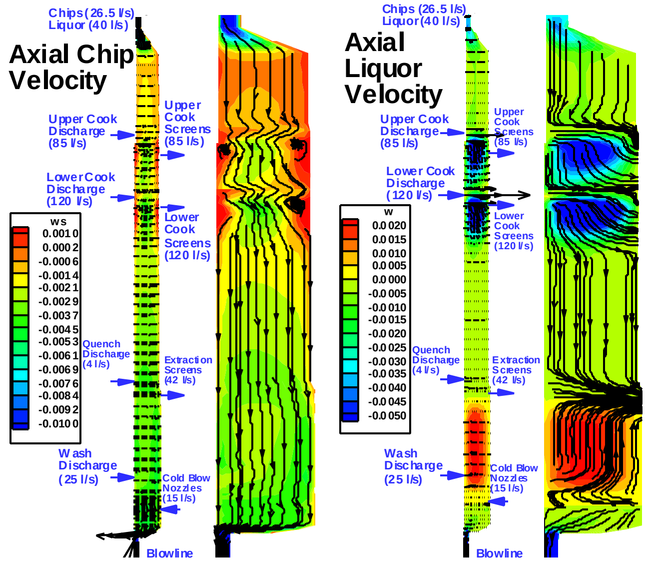
Convection | Stress tensor | Convection phase momentum exchange | Diffusion phase momentum | Body force

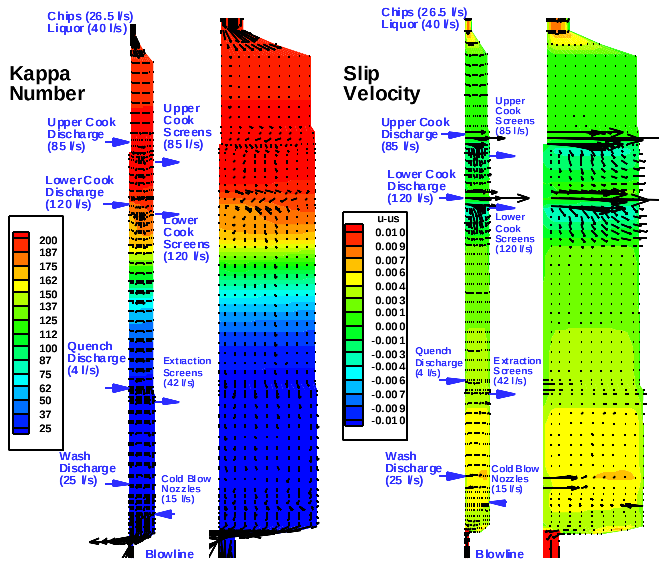
Solid

$$\frac{D\varepsilon_2\bar{\rho}_f\bar{V}_f}{Dt} = \nabla\cdot\varepsilon_2\bar{\sigma}_f - \frac{1}{U_0}\int_{S_{fs}}\bar{\rho}_f\bar{V}_f(\bar{V}_f-u)\cdot\nu_f\,dS + \frac{1}{U_0}\int_{S_{fs}}\sigma\cdot\nu\,dS + \varepsilon_2\bar{\rho}_f\bar{F}_f$$

Why Model a Digester?: Digesters represent huge capital investment for mills. Pulp quality is dependent in part on the flow and temperature distribution within the digester and on the presence of flow channelling and stagnation regions. High corrosion rates in digesters significantly reduce their life. Understanding the flow field and chemical species distribution inside the digester can help address issues of corrosion. By simulating the entire process, it is possible to improve process control and pulp quality, enhance equipment performance and reliability, identify inadequate operating procedures and propose alternatives, and reduce risks involved in additional capital expenditures by impacting the decision-making process.

Sample Results: The attached results show the flow distribution in the axial direction for the chips and for the liquor, the Kappa number, and the slip velocity between phases. Velocity contours in the axial direction and velocity vectors are shown for each phase. Each result is duplicated with the scale in the radial direction increased by a factor of 4. Results show a relatively strong recirculation region at the start of the cooking stage for both the chip and liquor velocities. The recirculation is in the clockwise direction because the upper and lower cook discharge orifices inject liquor at a higher elevation as compared to the upper and lower cook screens. The Kappa number varies from 200 to 25 with most of the change occurring above the extraction screens. The wash flow discharge does not penetrate far into the digester, flowing upwards instead and staying closer to the discharge pipe before turning towards the extraction screens. Chip axial flow velocities are smaller than the liquor velocities in the upward direction and larger in the downward direction.





Model Application: The model is licensed to Process Simulations Limited (www.psl.bc.ca) which specialises in process modelling in the pulp and paper industry.

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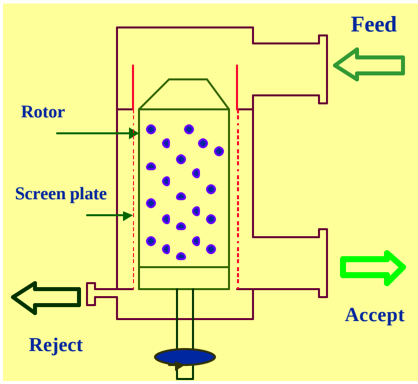
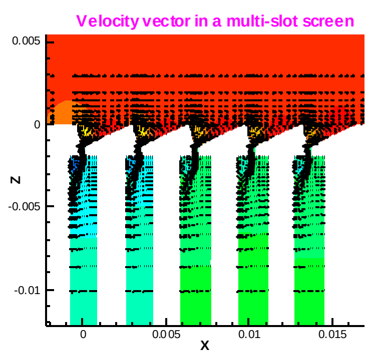
Screen Fractionation

Screens are used to remove shives from pulp and can also be used to fractionate fibres. The main objective of the fibre fractionation screen program by the UBC numerical group is to develop computational methods and tools to simulate the motion of fibres in screens. This requires a detailed simulation of the flow field, including the calculation of the vorticity and stress tensors in the flow and the prediction of the motion of a flexible fibre in a general three-dimensional shear flow.



Fractionation Model: Flow calculations are performed using a 3-D curvilinear solver developed at UBC. A sample flow distribution in a multi-screen slot is shown below. The flow field is then coupled to a detailed flexible fibre model. Each fibre is modelled as a chain of spheroids linked together by joints. The translational and rotational equations of motion for each spheroid in the chain are solved for multiple fibres injected into the screen. A wall function is included in the model. The fractionation program in screens is funded by *FRBC*.



Model Application: The application of this new tool can lead to better control of pulp fibre fractionation equipment. The specific objective of this work is to address the increasing need to predict and control the fractionation of fibres according to species and fibre characteristics.

Sample Results: The model can be used to study the influence of fibre length, fibre flexibility, flow condition, screen dimensions, and slot geometry on screening. The figure below shows the four main types of fibre behaviour occurring in screens.

The benefits from this new modelling tool are made available to manufacturers of screens, pulp and paper companies, and research organisations.

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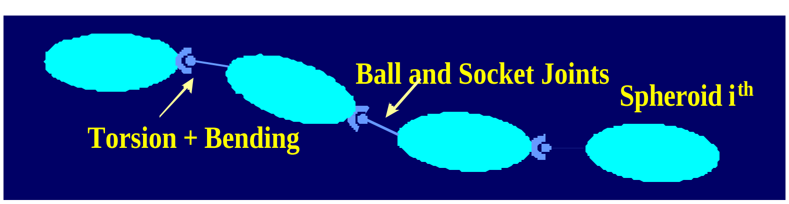
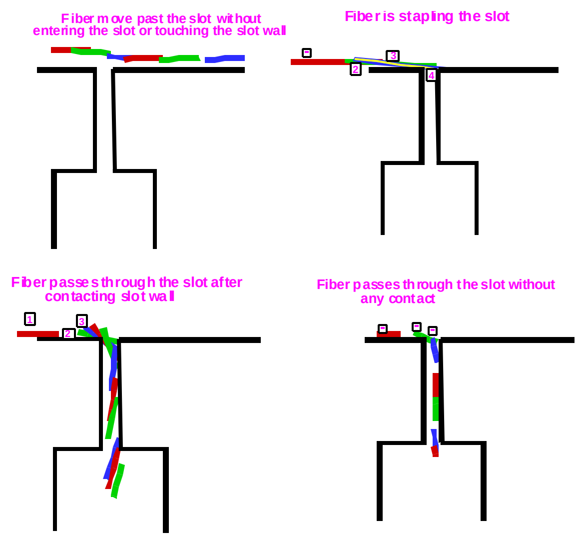
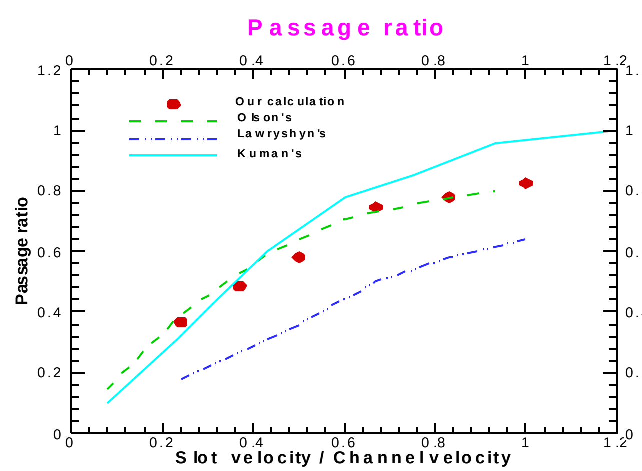




Fibre passage behaviour through a screen slot



Passage ratio as function of slot velocity

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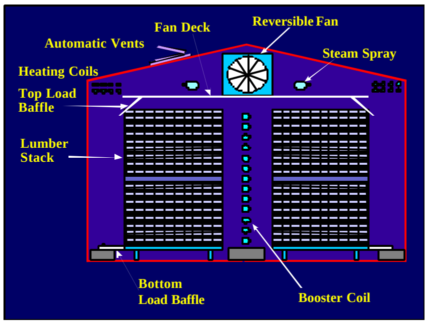
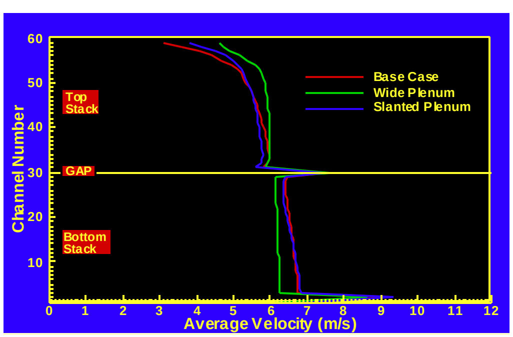
Wood Kilns



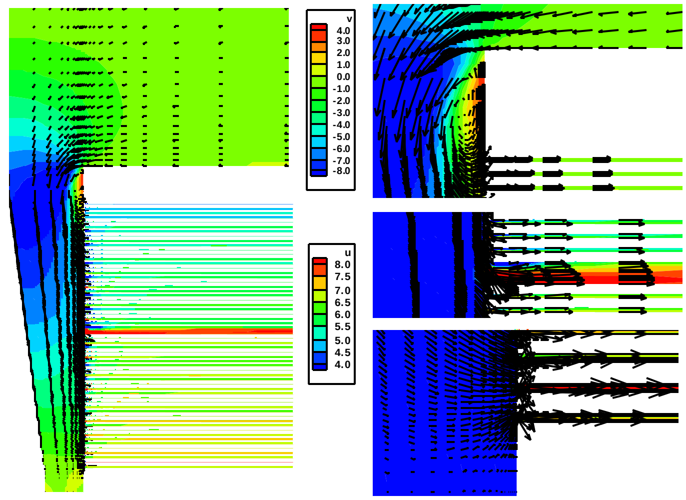
A wood kiln provides control over the temperature, humidity, and air circulation for drying lumber. An optimised kiln should remove water inside the wood in the least amount of time to a desired moisture content with a low moisture variation, while utilising the least amount of energy, and avoiding wood drying defects, which can occur during convection drying. Drying defects such as checking, discoloration, warp, and uneven moisture content account for the largest cost in kiln operations. The uniformity of drying and the quality of the wood in a kiln are strongly influenced by the drying schedule and by the uniformity of the airflow. The uniformity of the airflow has an important effect on the final moisture distribution and the reduction of wood defects and is influenced by such parameters as the geometry of the kiln plenum, air ducts, roof design, the proper stacking of each wood package, and lumber dimensional control. A uniform airflow ensures uniformity of drying temperature and humidity, avoids moisture build-up through regions of stagnation in part of the packages, and minimises prolonged periods of moisture equalisation. Minimisation of airflow variations requires a proper understanding of the mechanisms that contribute to airflow non-uniformities.

UBC Wood Kiln Model: To achieve the optimisation of a drying kiln and to improve the quality of wood products, simultaneous modelling of the mass transfer and heat transfer in the wood and in the air



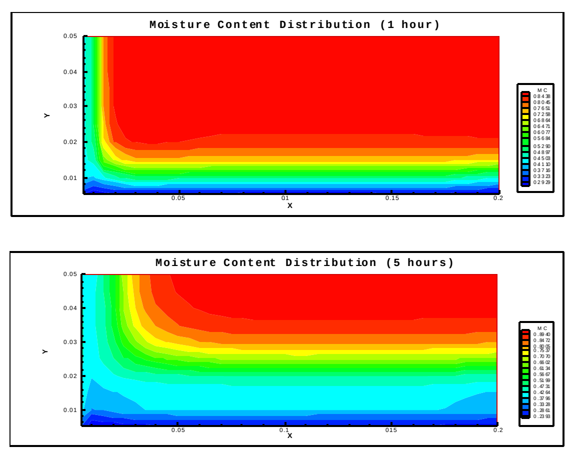
Effect of plenum geometry on airflow distribution in 2 packages

is required, as these factors are interdependent. The UBC modelling group is currently developing a kiln model to optimise kiln designs, help improve kiln operations, and address the requirements of the industry regarding the reduction of wood defects and the lowering of the deviation in moisture content. A three-dimensional airflow kiln model has been



Flow variation in tapered plenum and wood packages

developed in conjunction with a three-dimensional wood-drying model. Coupling between the airflow and wood drying models and the development of statistical variations in wood package geometry and wood properties are currently under development. The wood kiln program is funded by *NSERC*.



Moisture distribution in wood exposed to air

Model Outcome: The expected outcome of this research program is a tool that can be used to increase energy efficiencies, optimise kiln operations, and improve product quality. Currently, the model is able to address the influence of kiln design on air uniformity and drying conditions. Problems resulting from improper packaging of the lumber and the influence of the air velocity, temperature, and humidity control on the moisture distribution within lumber packages during the drying schedule will soon be available. Process Simulations Limited (www.psl.bc.ca) is currently applying the airflow model to the wood industry.

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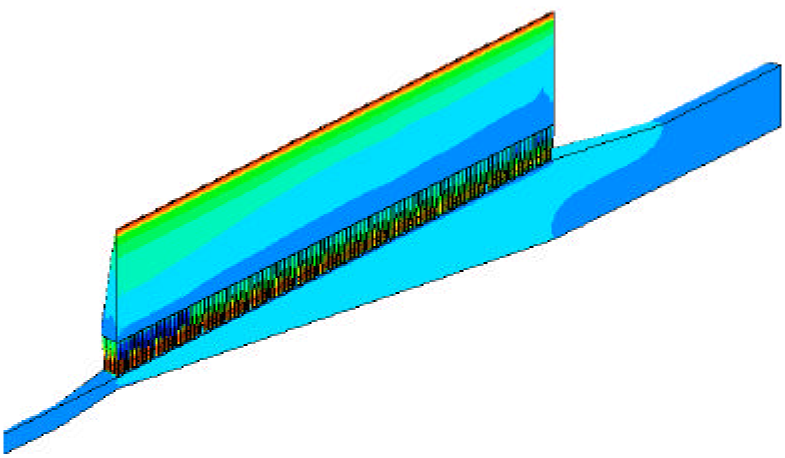
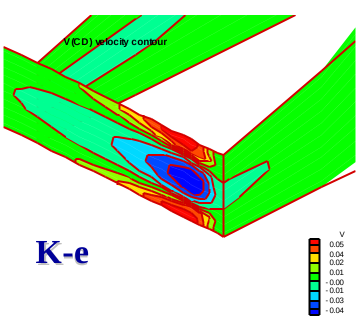
HEADBOXES

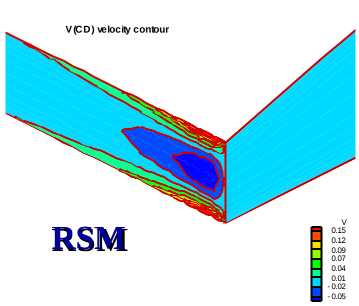
Property variations in the paper sheet often originate from the headbox. Controlling basis weight variations in the cross-machine direction and obtain a desired MD/CD ratio can significantly improve profit margins. Traditionally, headbox designs and modifications have been based on experience and physical modelling. Because of the complexity of the geometry and the three dimensional nature of the flow field, such an approach is often incomplete. Headbox modelling can provide a comprehensive picture of flow non-uniformity at the slice exit for a given paper speed range. Pressure and flow variations inside the headbox are obtained.



HEADBOX TOOLS: The UBC modelling group has been working on developing a 3-D headbox model including the ability to model the complete headbox with all its diffuser tubes. In addition, the model can use non-linear turbulence models like the algebraic stress model. A Large Eddy Simulation model of the convergence section is currently being developed. A physical model of the convergence section of a hydraulic headbox has been built to validate results. Laser Doppler Velocimetry is used to measure mean and fluctuating components of the velocity at different locations. Fibres are visualised using photographic techniques. The model is also coupled to a flexible fibre motion model to understand fluid-fibre interactions in the headbox and to predict fibre angle distribution at the slice. *FRBC*, *NSERC*, and *PSL* fund the headbox program.

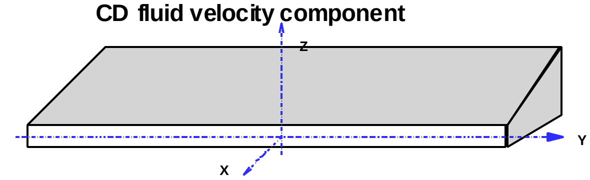


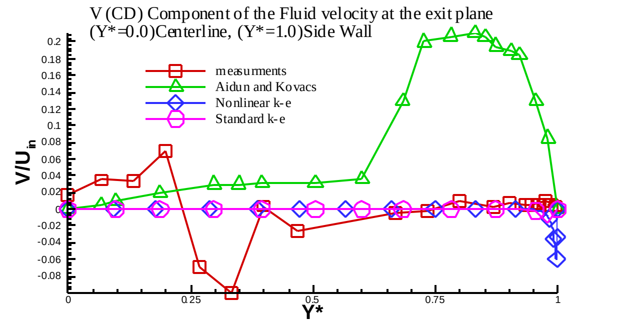
K-e



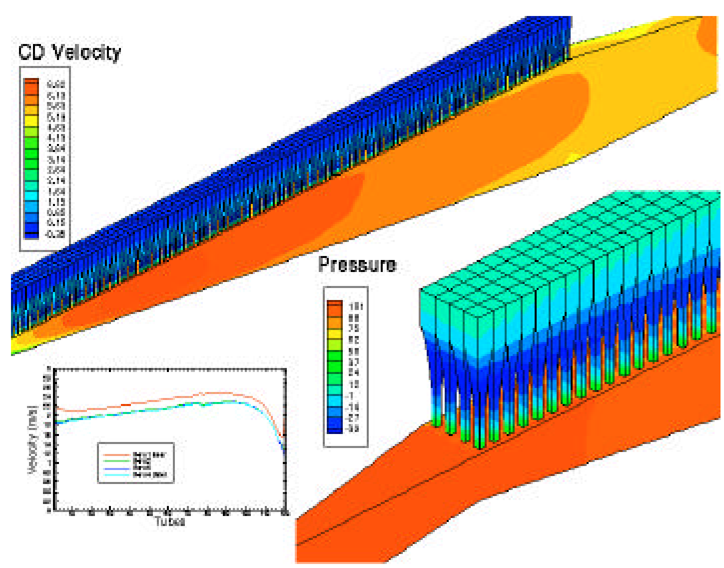
RSM

CD fluid velocity component





MODEL USAGE: The computational model can be used to identify potential sheet-forming problems, increase capacity of the headbox without adversely affecting paper quality, improve paper quality, analyse the existing flow inside a headbox, evaluate the effect of the approach and exit piping on the flow distribution in the headbox, identify the root cause of flow non-uniformities, analyse planned headbox retrofits, and suggest operational and design changes to meet production goals. The simulation results provide a comprehensive understanding of the headbox and a reliable basis for optimisation. Any proposed changes can be evaluated in advance using the model, so that risks in the decision-making process can be minimised.



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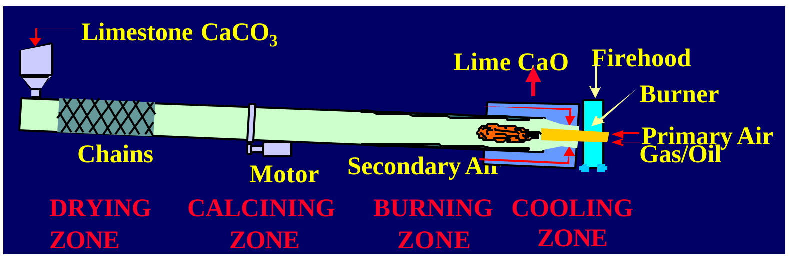
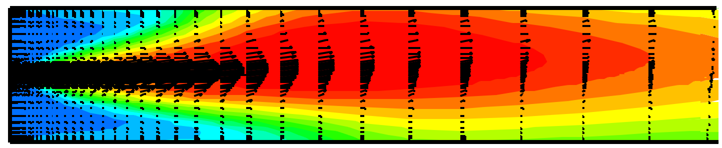
LIME KILNS

The function of the lime kiln in pulp and paper is to convert $CaCO_3$ back into CaO for reuse in the causticizing process. The lime kiln involves complicated processes, including flow, heat and mass transfer, combustion of fuel, drying of lime mud, and calcining of $CaCO_3$. It is important to understand these processes to optimise the operation of the lime kiln, diagnose operational problems, improve energy consumption, increase production, lower emissions, increase refractory life, and reduce instabilities.



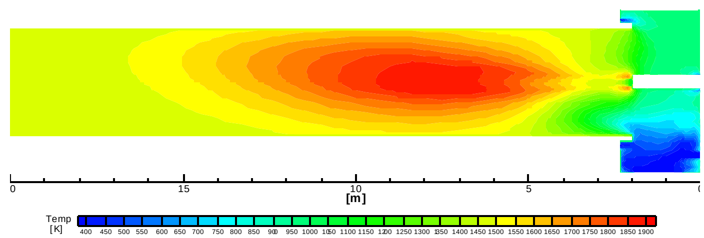
PROCESS MODEL: The UBC modelling group is currently working to complete a 3-D steady-state computational model to predict the flow and heat transfer in a lime kiln. The model uses block-structure body-fitted coordinates with domain segmentation, models combustion and radiation, and will eventually incorporate the modelling of the non-Newtonian lime mud. Currently, the model includes radiation, combustion of natural gas and oil, buoyancy effects, and features complex geometry capability. Separate equations are solved for O_2, N_2, H_2, CO, CO_2, H_2O and CH_4. The k-ε turbulence model is used to compute the turbulence and the Magnussen combustion model is used for the gas combustion. The



Flow vectors in an experimental kiln

model is currently used to model the flow, heat transfer, and combustion in the lime kiln, and to analyse the influence on the flame of secondary flows from the hood and the primary air from the burner. The lime kiln program is funded by *NSERC*.

MODEL USAGE: The flow field, the temperature distribution, and the chemical species concentration distributions are used to predict the emissions for various input conditions, kiln geometries, and burner designs.



Temperature distribution in the lime kiln

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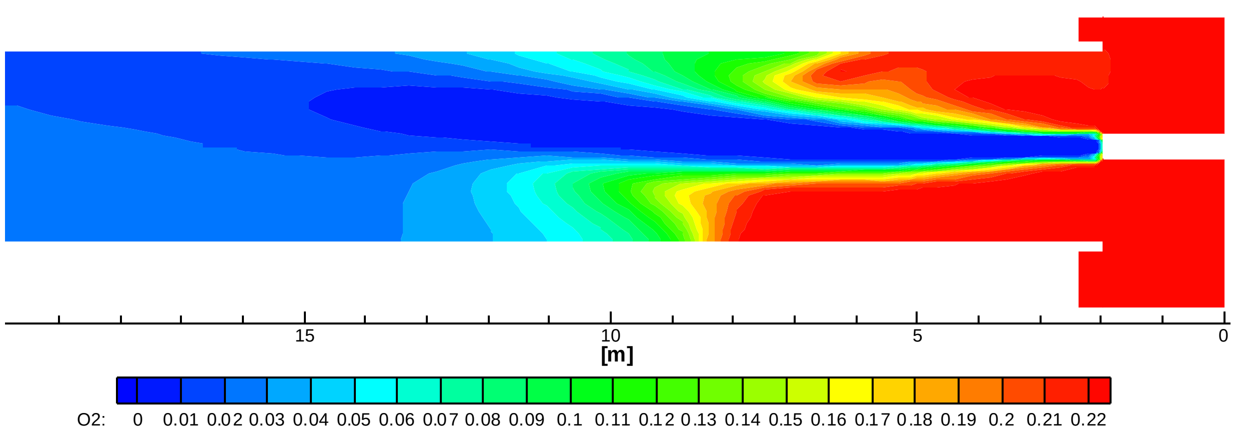

Oxygen concentration distribution in the lime kiln

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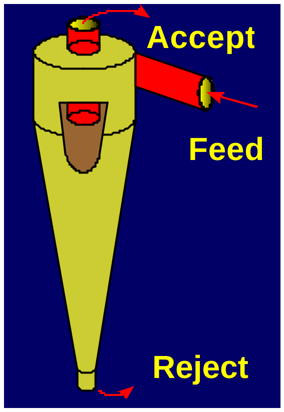
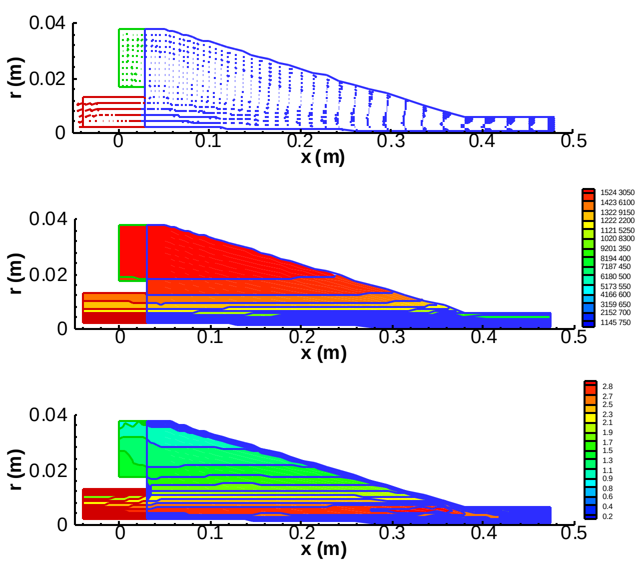
Fellow C.A.S.I

Hydrocyclones

Hydrocyclones use the principle of centrifugal separation to remove or classify solid particles from a fluid, based on size, shape, and density. In order to improve the design and operation of hydrocyclones, it is important to have a good understanding of the flow and particle motion. The UBC numerical modelling group has developed a fractionation model to predict particle separation and to model fractionation in hydrocyclones according to specific fibre properties, including but not restricted to coarseness.

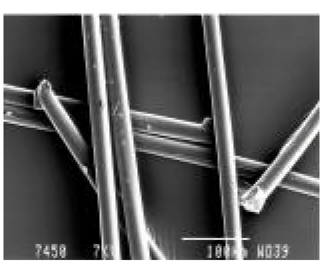


Fractionation Model: The first step is to predict the three-dimensional flow field, as the three-dimensional geometry near the inlet pipe influences significantly the accuracy of separation predictions.

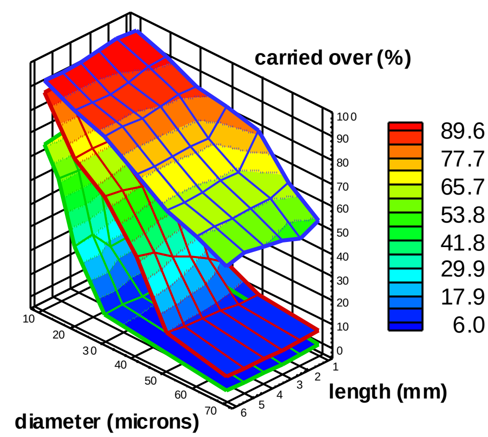


Velocity, pressures, and swirl in a hydrocyclone

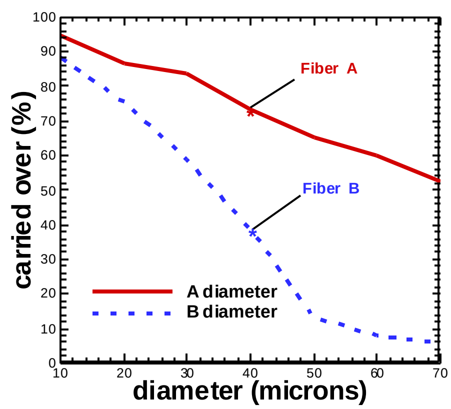
Computation of the flow filed in the hydrocyclone is done using block structured curvilinear grids; turbulence is modelled using a k-ε model specially modified for highly curved turbulent flows. The swirling flow pattern, imparted to the incoming fluid, is the dominant flow feature in the hydrocyclone. Several minor flow patterns are also associated with the rotational flow and influence the trajectories of the particles. The computation of the liquid-phase velocities and particle motion is carried out independently. Fibres experience a centrifugal force in the rotational flow field, which is balanced by the pressure force and a drag force associated with the fibre motion. The centrifugal force is directly dependent on the tangential velocity and therefore its correct determination is critical in predicting the fractionation performance of hydrocyclones. The trajectories of the particles of different size, shape, and injection location can be calculated and the separation efficiency estimated. The hydrocyclone fractionation program is funded by *FRBC* and the *Wood Pulp Network*.



Model Usage: The developed model can be used to evaluate the influence on fractionation of fibre density, fibre diameter, fibre length, fibre specific surface, and coarseness, as shown in the figures below. In addition, the influence of hydrocyclone geometry and flow conditions on fractionation can be successfully address by the model. The model is licensed to Process Simulations Limited (www.psl.bc.ca).



Separation on diameter and length as function of density



Influence of particle diameter on fractionation

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