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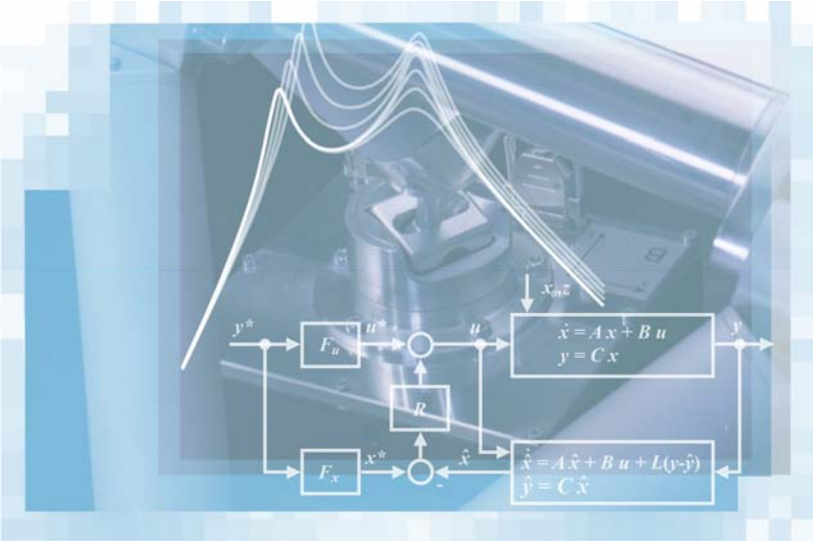
Modeling the Process of Drying Stationary Objects inside a Tumble Dryer Using COMSOL Multiphysics



Tarek H.M. Zeineldin

Outline

Introduction - Drying processes

Modeling Approach

- Transport Phenomena
- Governing Equations
- Boundary Conditions

Results and Validation

Summary and Conclusion

Introduction

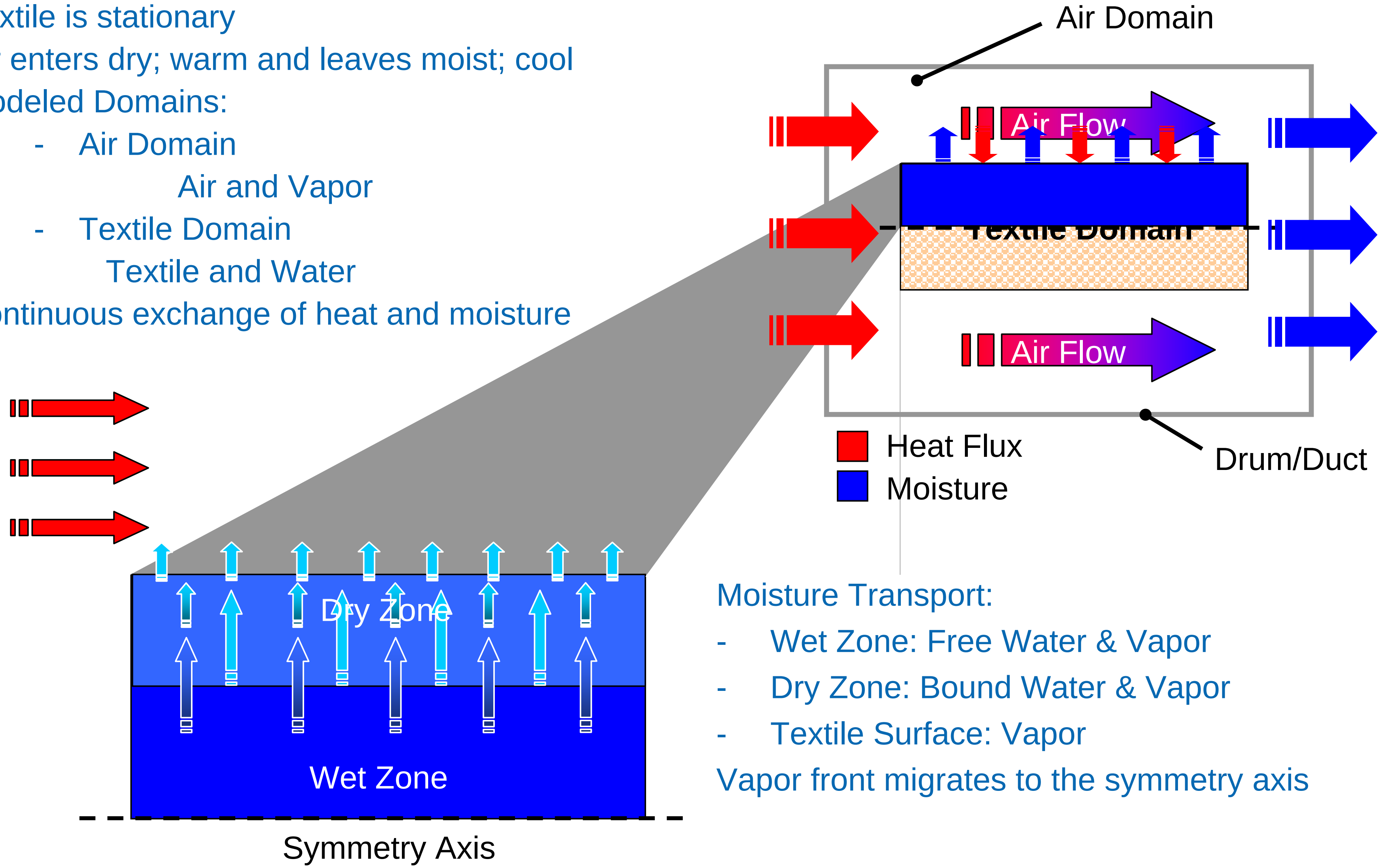
Textile is stationary

Air enters dry; warm and leaves moist; cool

Modeled Domains:

- Air Domain
    - Air and Vapor
- Textile Domain
    - Textile and Water

Continuous exchange of heat and moisture



Moisture Transport:

- Wet Zone: Free Water & Vapor
- Dry Zone: Bound Water & Vapor
- Textile Surface: Vapor

Vapor front migrates to the symmetry axis

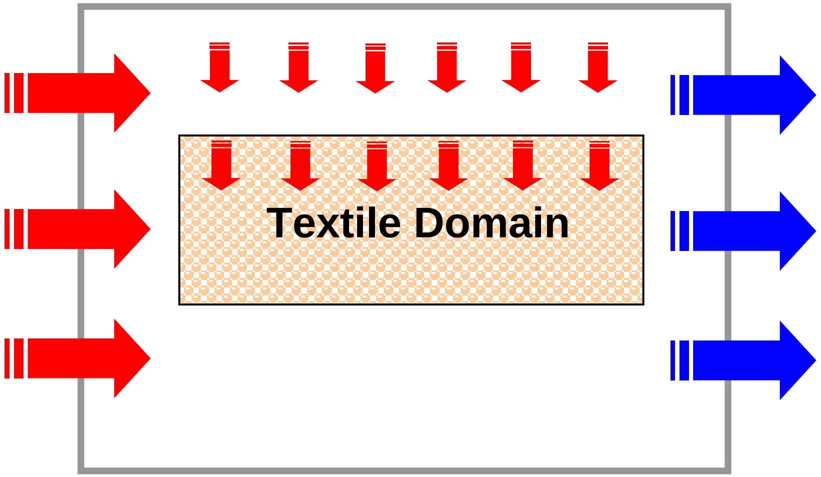
Modeling Approach

Transport phenomena – Textile (Energy)

- Energy Transport – Boundary Equation

$$k_t \cdot \nabla T = \underbrace{\alpha \cdot (T_a - T)}_{1} + \underbrace{\rho_w \cdot D_w \cdot \nabla X \cdot \Delta h_v}_{2}$$

1. Convective Energy
2. Energy lost due to phase change



- Energy Transport – Subdomain Equation

$$\rho_t \cdot c_{p,t} \cdot \frac{\partial T}{\partial t} = \underbrace{\nabla(k_t \cdot \nabla T)}_{1} - \underbrace{\dot{m}_{ev} \cdot \Delta h_v}_{2}$$

1. Conductive Energy
2. Energy lost due to phase change

k_t: Textile heat conductivity
T, T_a: Temperature of textile and air
α: Coefficient of heat transfer
ρ_w, ρ_t : Density of water and textile
D_w: Capillary conductivity
X: Textile moisture content
Δh_v: Enthalpy of evaporation
$c_{p,t}$: Textile specific heat capacity
m_{ev}: Evaporative mass flow rate

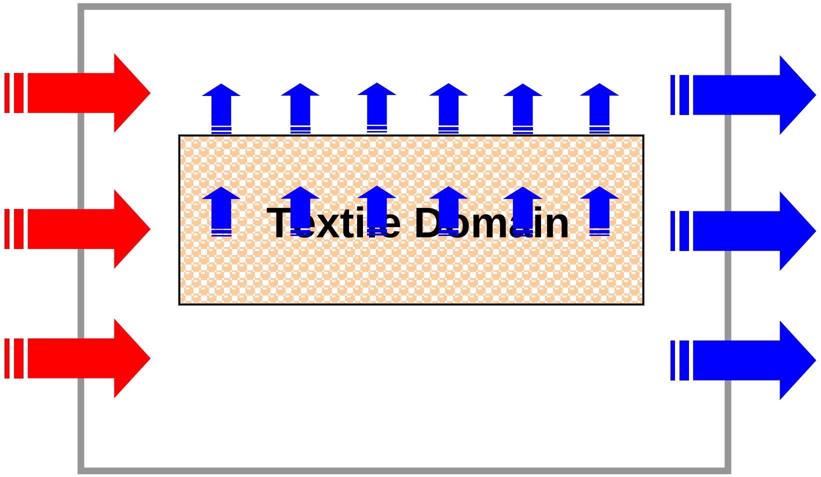
Modeling Approach

Transport phenomena – Textile (Mass)

- Mass Transport – Subdomain Equation

$$\rho_w \cdot \frac{\partial X}{\partial t} = \underbrace{\rho_w \cdot \nabla(D_w \cdot \nabla X)}_{1} - \underbrace{\dot{m}_{ev}}_{2}$$

1. Capillary conduction
2. Vapor conduction



- Mass Transport – Boundary Equation

$$\underbrace{\frac{D_v \cdot M_w}{R \cdot T} \cdot \nabla p_{v,t}}_{1} + \rho_w \cdot D_w \cdot \nabla X = \underbrace{\frac{\beta \cdot M_w}{R} \cdot \left(\frac{p_{v,a}}{T_a} - \frac{p_{v,t}}{T}\right)}_{2}$$

1. Vapor conduction
2. Vapor convection

D_v: Vapor diffusion coefficient
M_w: Water molecular weight
R: Universal gas constant
p_v: Vapor pressure
β : Coefficient of mass transfer

Modeling Approach

Transport phenomena – Air (Energy/Mass)

- E. Transport – Boundary Equation (1,2,3 & 4)

$$k_a \cdot \nabla T = \alpha \cdot (T - T_t) + \underbrace{\rho_a \cdot c_{p,a} \cdot v \cdot T}$$

- M. Transport – Boundary Equation (1,2,3 & 4)

$$\rho_v \cdot D_v \cdot \nabla X - \underbrace{u \cdot X} = \frac{\beta \cdot M_w}{R} \cdot \left(\frac{p_{v,a}}{T} - \frac{p_{v,t}}{T_t}\right) - \frac{D_v \cdot M_w}{R \cdot T_t} \cdot \nabla p_{v,t}$$

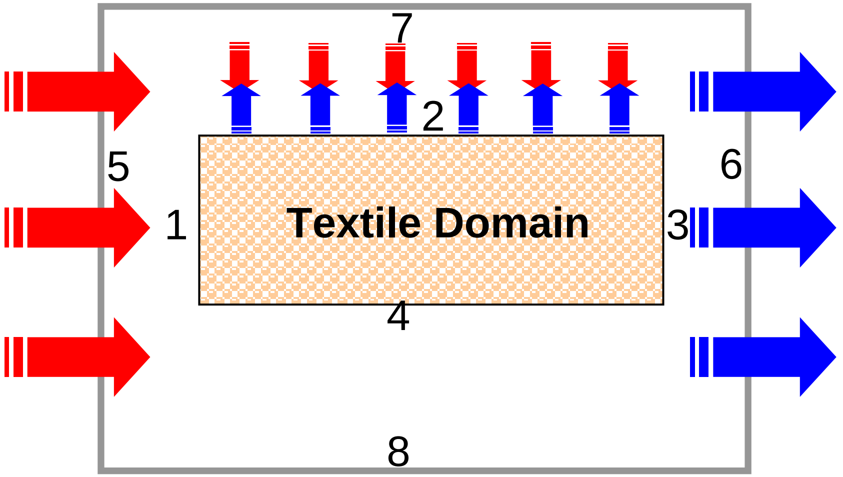
- Energy Transport – Subdomain Equation

$$\rho_a \cdot c_{p,a} \frac{\partial T}{\partial t} = \nabla(k_a \cdot \nabla T) - \underbrace{\rho_a \cdot c_{p,a} \cdot u \cdot \nabla T}$$

- Mass Transport – Subdomain Equation

$$\frac{\partial X}{\partial t} = \nabla(D_v \cdot \nabla X) - \underbrace{u \cdot \nabla X}$$

  - Additional convective terms due to air velocity



a: Air

u, v: Air velocity in the x and y direction

α: Coefficient of heat transfer

Modeling Approach

Transport phenomena – Air (Energy/Mass)

- Boundary Equations (5)

$$T = T_0$$

$$X = X_0$$

- Boundary Equations (6)

$$k_a \cdot \nabla T = 0$$

$$D_v \cdot \nabla X = 0$$

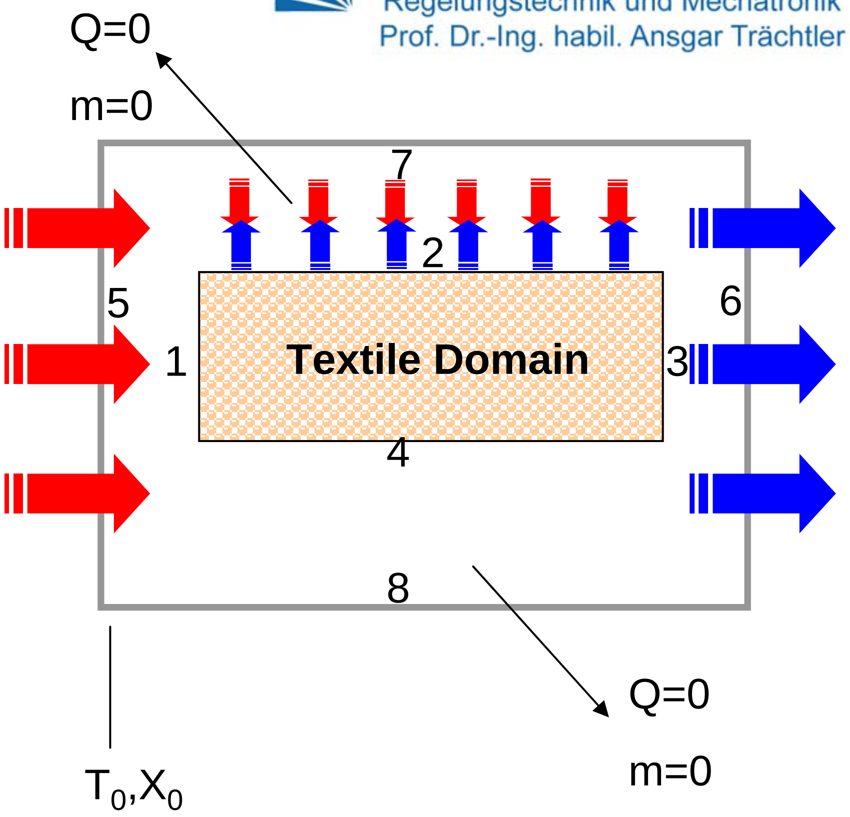
  - Convective flux

- Boundary Equations (7 & 8)

$$k_a \cdot \nabla T - \rho_a \cdot c_{p,a} \cdot u \cdot T = 0$$

$$D_v \cdot \nabla X - u \cdot X = 0$$

  - Insulation



Modeling Approach

Transport phenomena – Air (Momentum)

- Boundary Equations (1,2,3,4,7 & 8)

$$u = 0$$

  - No slip

- Boundary Equation (5)

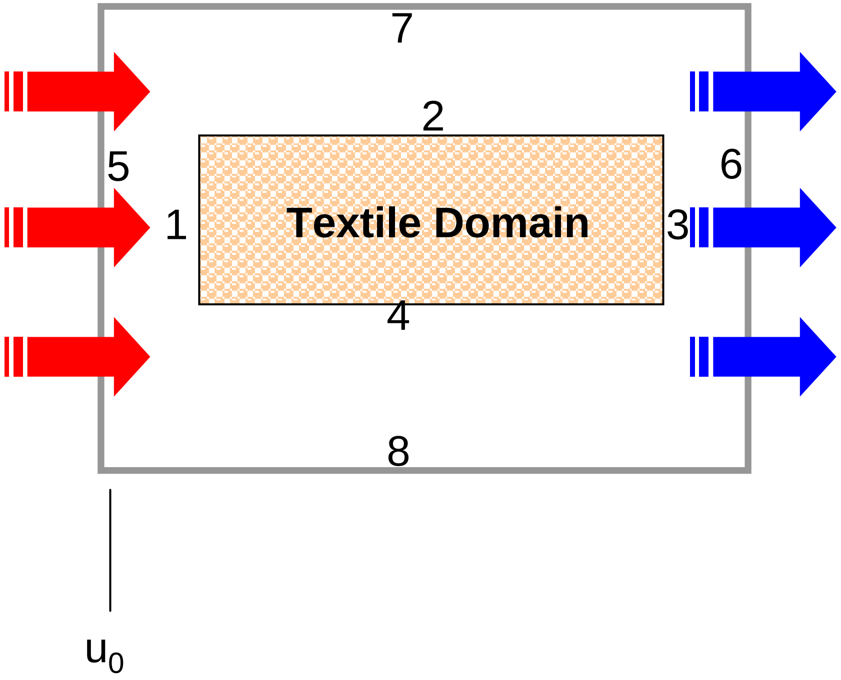
$$u = u_0$$

  - Fully developed flow

- Boundary Equation (6)

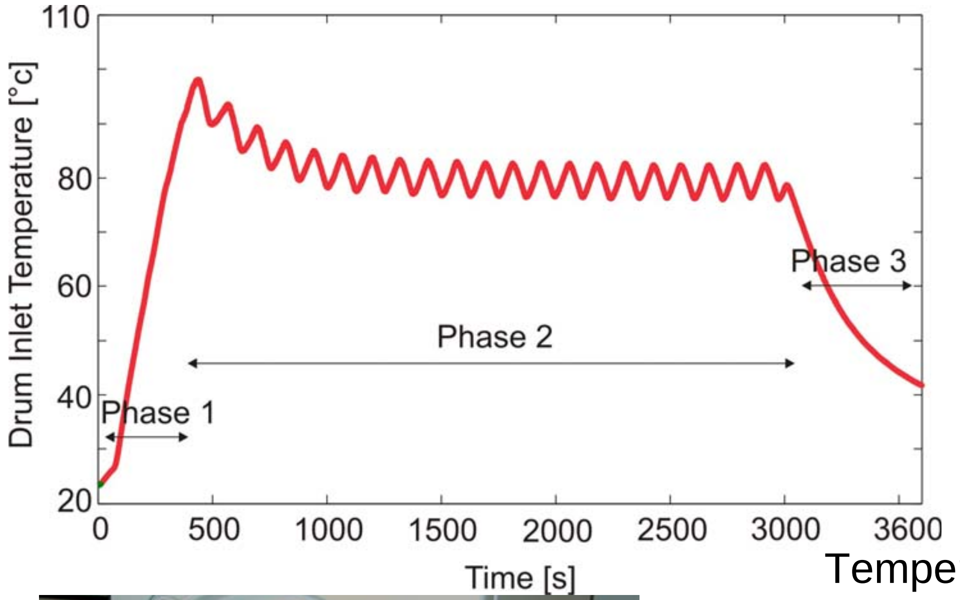
$$p = p_0$$

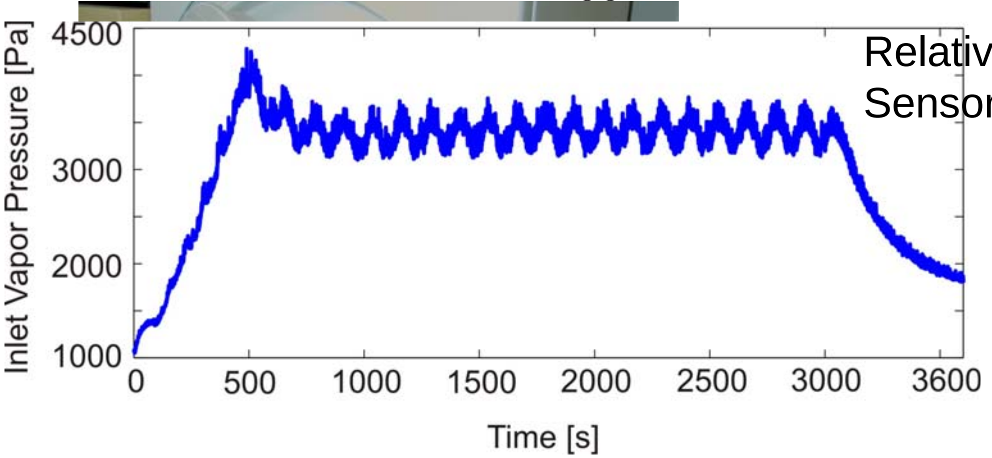
  - Outflow

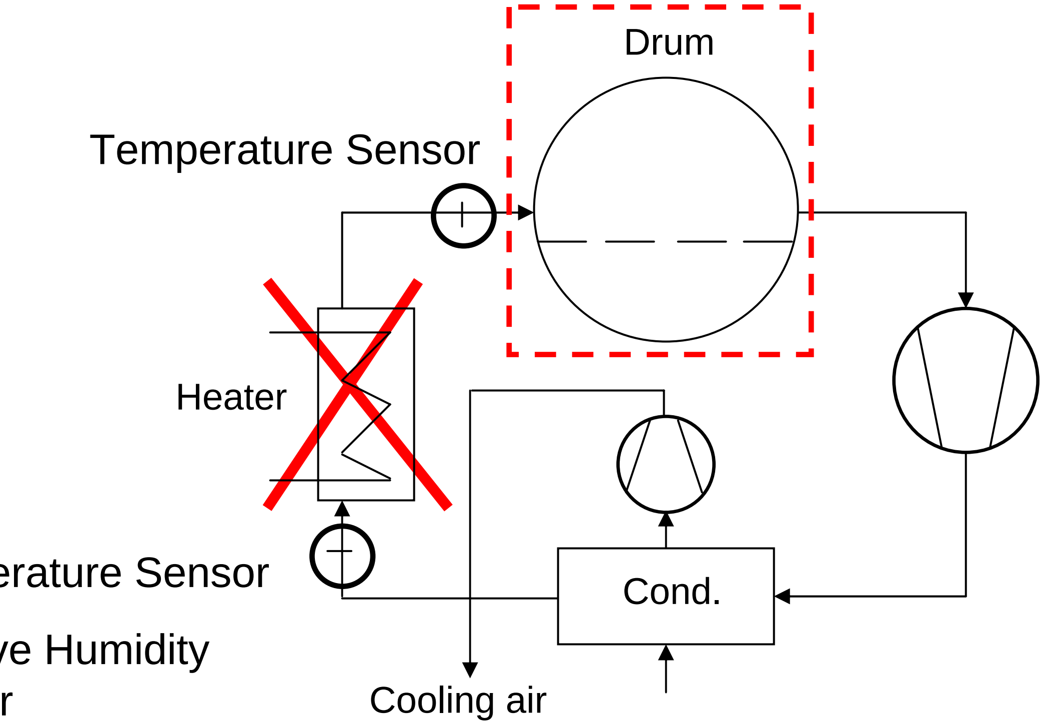


Results and Validation

Test bench







Schematic of the test bench and sensor position

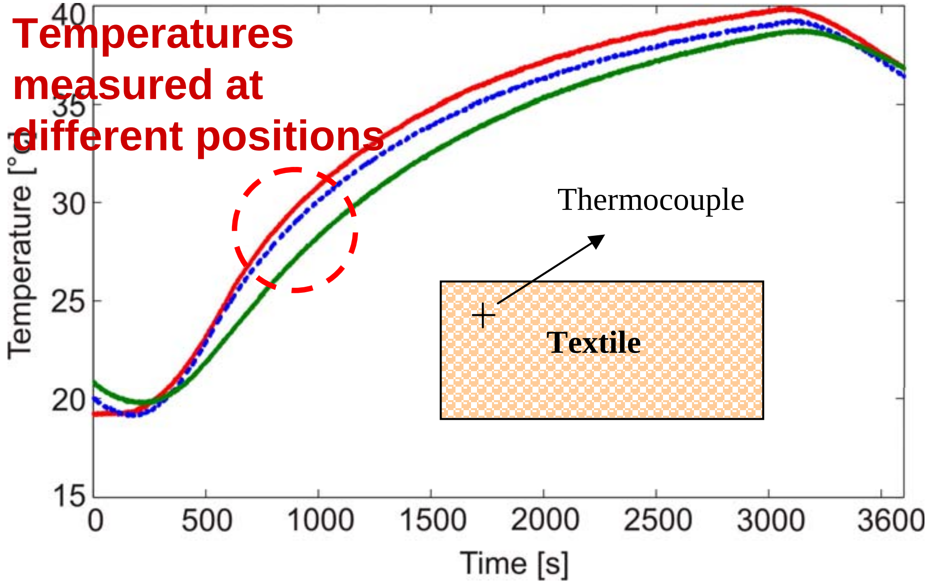
Results and Validation

Modeled phenomena:

- Energy transport - Textile
- Mass transport - Textile

Simulation conditions:

- 10x7mm thick layers of cotton textile
- 0.6 initial moisture content
- 2.9KW commercial condenser dryer as test bench
- 120 m^3/hr volume flow rate
- Textile temperature measured for validation
- Temperature and vapor pressure measured at drum inlet as boundary conditions
- 1/3 Real-time



Temperatures measured at different positions

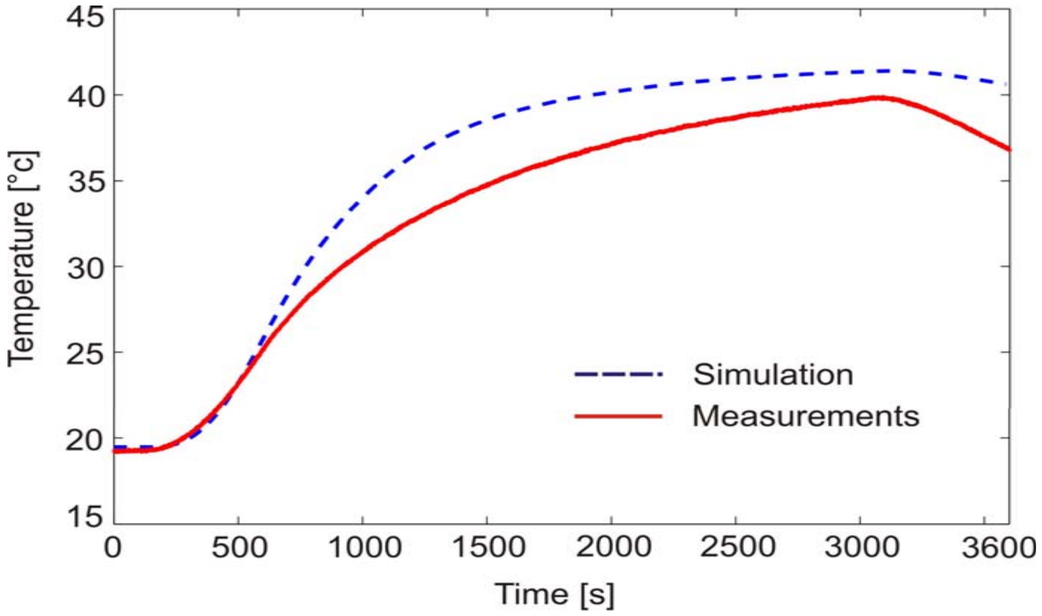
Measured textile temperature: 3 measurement series

Results and Validation

Simulation results

5°c max. temperature error

- Misplacement of the thermocouple (human error)
- Thermocouple temperature averaging affect
- Nonuniform textile geometry/surface
- Sensitivity of relative humidity sensors to water drops
- Temperature along the boundaries was held constant (Air flow was not simulated)



Simulation results vs. measurements

Results and Validation

Model extension

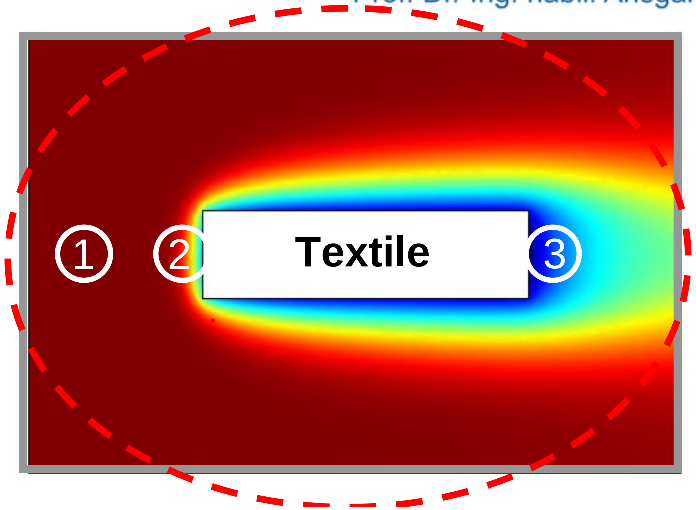
Modeled phenomena:

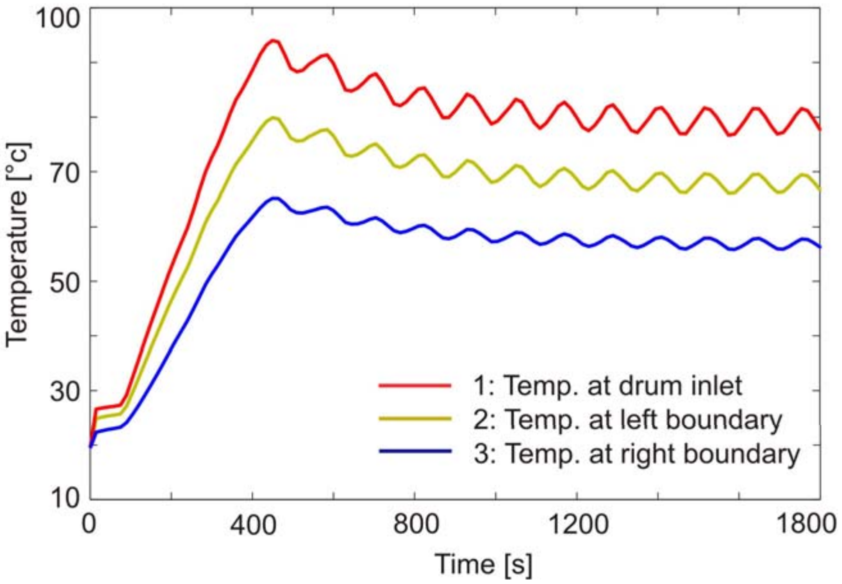
- Energy transport - Textile
- Mass transport - Textile
- Energy transport - Air
- Mass transport - Air
- Momentum transport - Air

Simulation conditions:

- 4x1mm thick layers of cotton textile
- 0.6 initial moisture content
- 120 m3/hr volume flow rate
- Temperature & vapor pressure given at drum inlet
- Reduced dimensions due to limited computer power

17 times smaller than the original volume





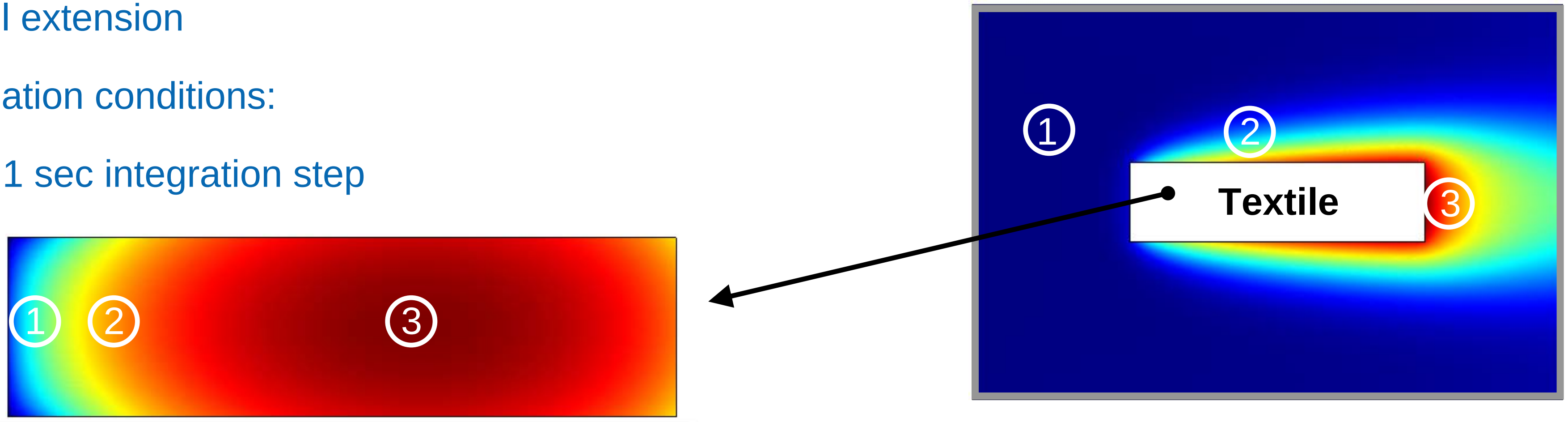
Difference in temperature between inlet and boundaries.

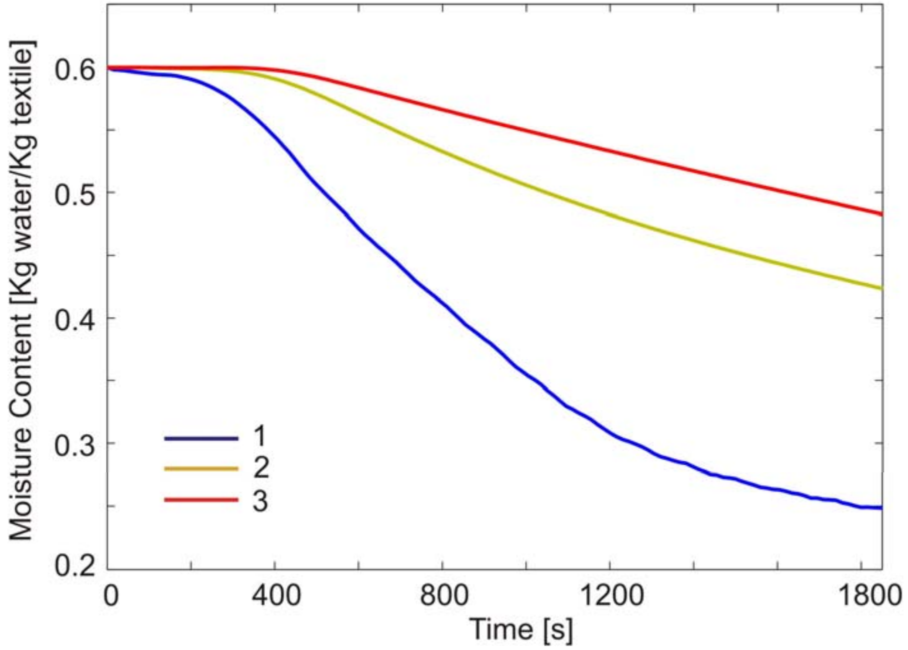
Results and Validation

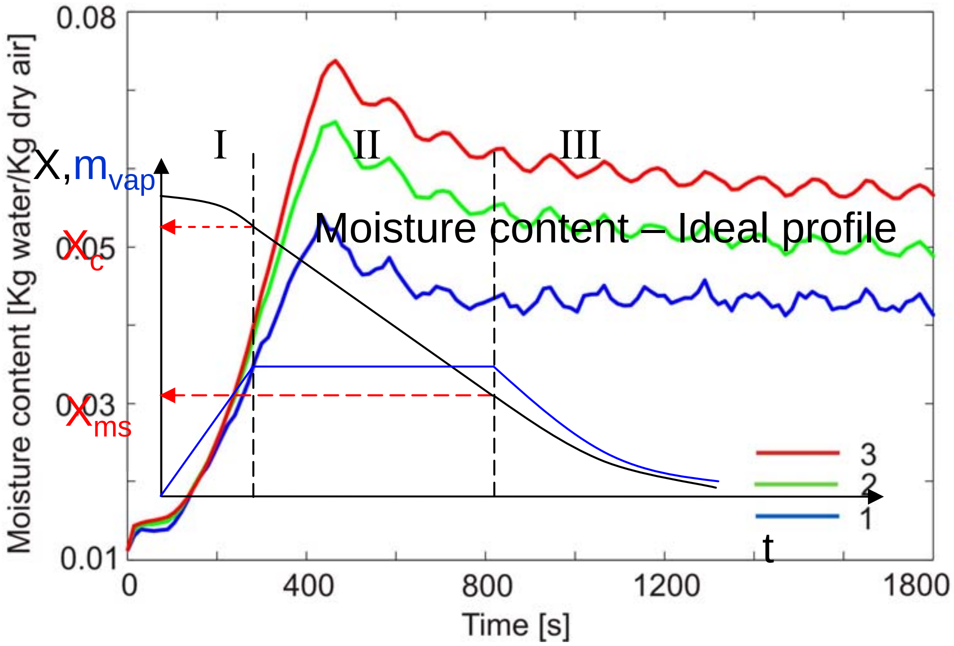
Model extension

Simulation conditions:

- 0.1 sec integration step







Results and Validation

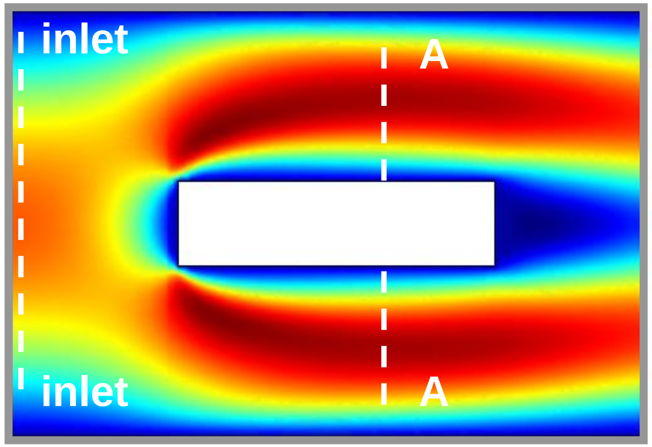
Model B

- Sharp curves due to large integration steps
- Strong tendency to enhancement by decreasing the integration step
- Agreement with the ideal drying curves

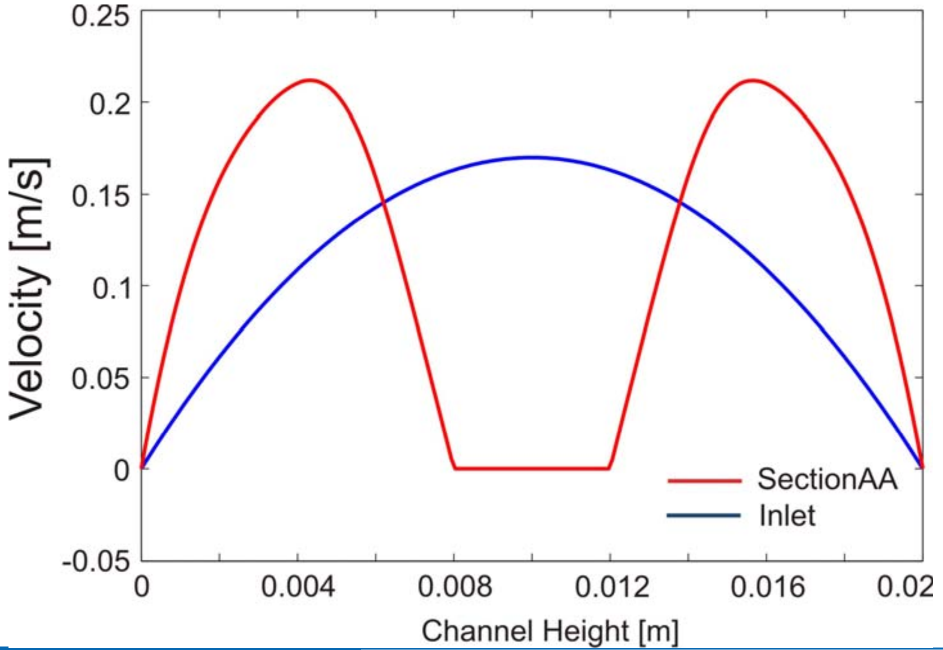
Model B

Momentum transport

- Reduced size of the drum in order to meet the required mesh resolution
- Assumed laminar flow at the inlet
- Increase in velocity at lower cross sectional areas



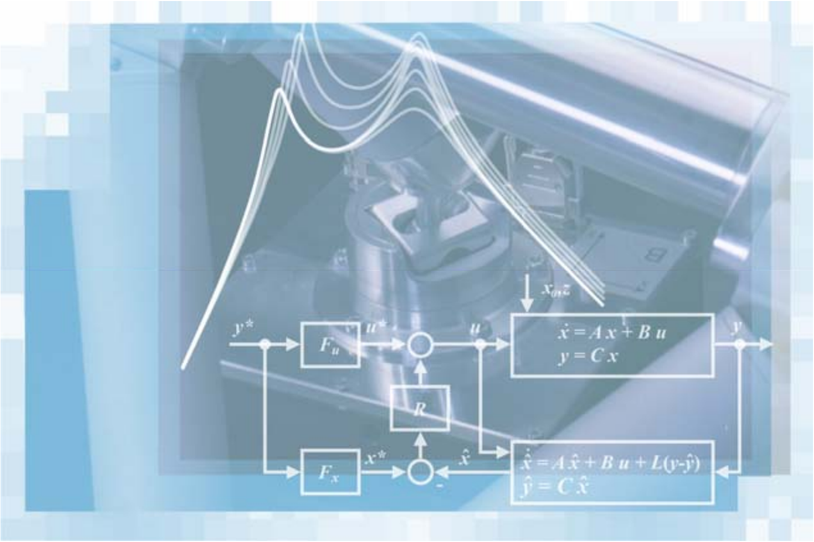
Velocity profile along the drum



Summary and Conclusion

- Two successful models of stationary drying processes were built with COMSOL Multiphysics
- Successful application of governing equations in COMSOL Multiphysics despite nonlinearity
- Successful coupling of the five main drying transport phenomena
- Simulation results agreement with measurements
- Agreement with ideal drying curves
- Promising tendency for result enhancement with decreasing integration steps
- Using smaller thermocouples for future model validation
- Future opportunity of modeling the original geometry on increasing computer power

Thank You for Your Attention



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