An Investigation of Heat Transfer during Curing of Thin Carbon Fiber Composite tubes

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Motivation

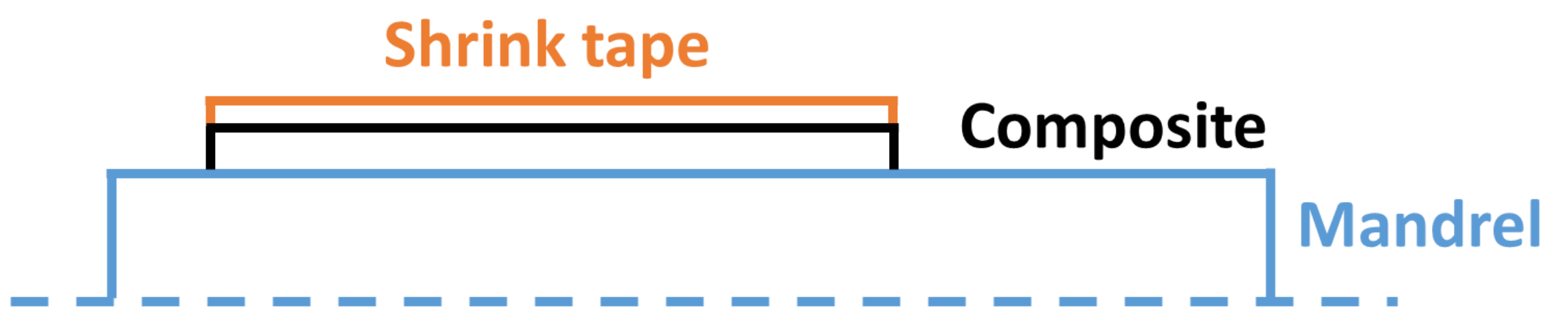
Curing is an important step in production of carbon fiber tubes and has an impact on the mechanical performance of the final product. One of the main problems due to uncontrolled curing is having incomplete cured matrix. Heat transfer analysis during curing allows monitoring the behaviour of the system and defining the critical parameters to optimize this process.

Objective

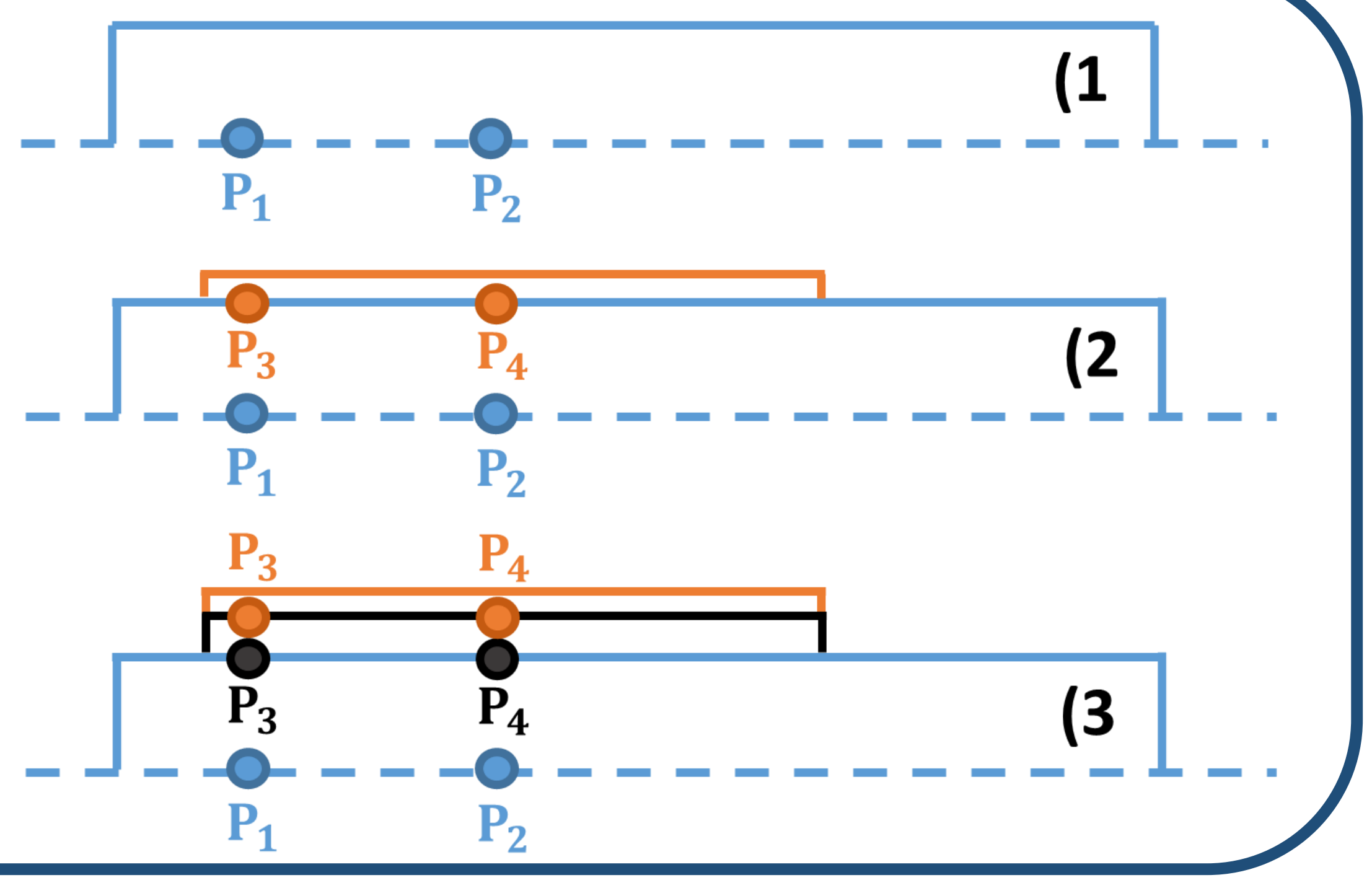
- Model the cure kinetics of thermoset epoxy resin, TP135
- Establish a heat transfer analysis for composite tubes based on prepreg technology
- Monitor and model the real cure cycle using environmental chamber
- Implement the method at NTPT Poland using industrial ovens

Materials

Application	Material	Length × Thickness (mm^2)
Mandrel	Stainless Steel (Abbreviation 1.0737)	600 × 5
Shrink tape	PET	340 × 0.3
Composite tube	TP135 (Epoxy Resin)	340 × 0.5
	T800H CF	



Axisymmetric scheme



Main Results

- Cure Kinetics of TP135 was modeled based on the autocatalytic model

$$\frac{d\alpha}{dt} = 2.81 \times \exp\left(-\frac{77.53}{RT}\right) \times \alpha^{\begin{cases}0.182, & T<60℃\\ 0.0183T_c-0.9334, & T\geq 60℃\end{cases}} \times (1-\alpha)^{-0.0185T_c+3.5481}, \quad \alpha \geq 0.022,\ T \geq 125℃$$

- Heat transfer coefficient (h) of all three systems, while using **environmental chamber**, was experimentally measured to be 35 $\frac{W}{m^2.K}$
  - → The environmental chamber transfers the heat **efficiently**. ($1 \leq h \leq 40\ \frac{W}{m^2.K}$ for natural convection in gas)[1]
  - → Shrink tape and composite layers are not strong heat barriers
- h of system, using **industrial oven:**
  - → NTPT industrial oven was **less efficient** in transferring heat than the environmental chamber
  - → Introducing large mass of objects **reduced** the efficiency of oven for transferring heat

Industrial oven capacity filled (%)	h_{top} ($\frac{W}{m^2.K}$)	h_{bottom} ($\frac{W}{m^2.K}$)
0	15	15
100	6	8

Conclusion

A **methodology** to monitor and analyze the **heat transfer during curing** of thin carbon fiber tubes in **industrial scale** was established.

Methodology

Thermochemical energy balance equation: $$\rho_c . C_{P_c} . \frac{\partial T}{\partial t} = \nabla(k_c . \nabla T) + \rho_r . v_r . H_r \frac{d\alpha}{dt}$$ [2]

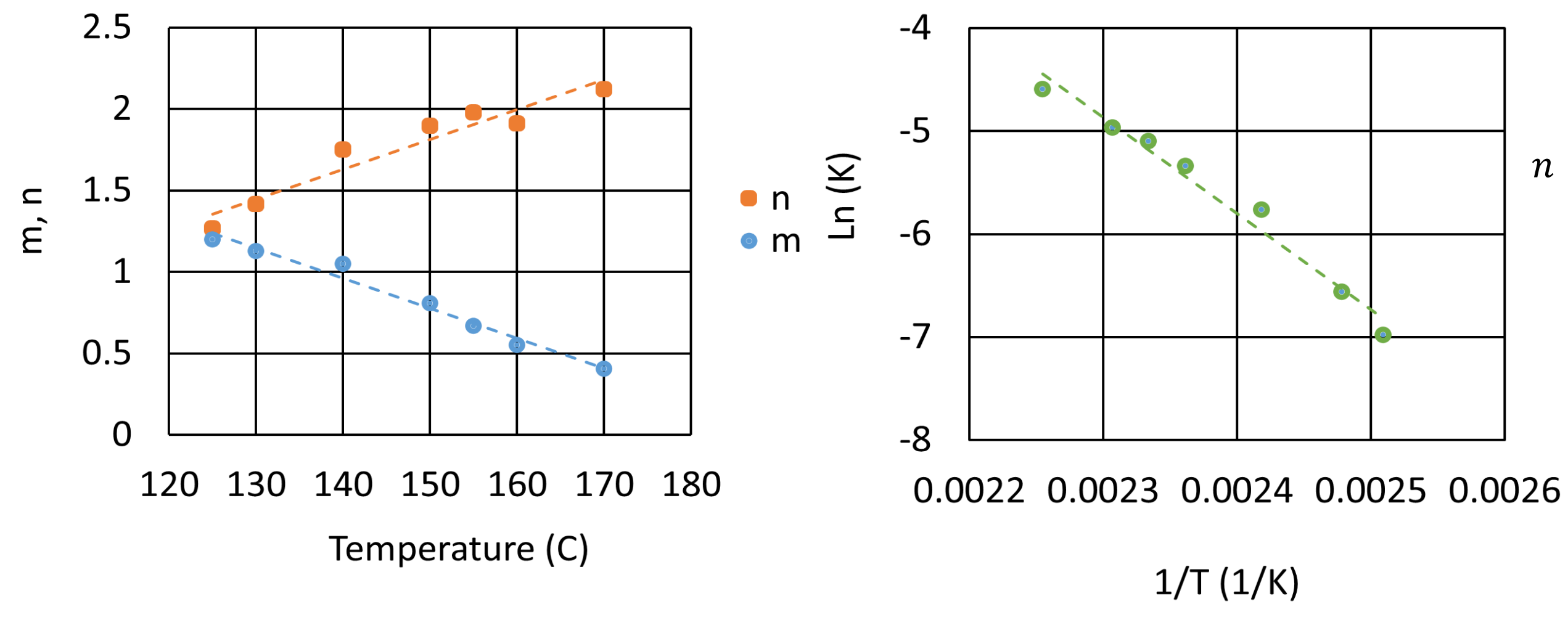
C_{p_c}: specific heat capacity of composite ($^J/_{kg.K}$), H_r: heat of reaction per unit mass of resin ($^J/_g$), k_c: thermal conductivity of composite ($^W/_{m.K}$), T: Temperature (°C), t: time (min), v_r: resin volume fraction, α: Degree of cure, $\frac{d\alpha}{dt}$: curing reaction rate, ρ_c: density of composite (kg/m^3), ρ_r: density of resin (kg/m^3)

Cure Kinetics Modeling

Autocatalytic model:

- $\frac{d\alpha}{dt} = K.\alpha^m.(1-\alpha)^n$, where $K = A^*.\exp\left(\frac{-E_a}{RT}\right)$ [2]

K: reaction rate constant, f(α): conversion dependent function, A^*: pre-exponential factor, E_a: activation energy (kJ/mol), R: gas constant (J/mol)



$$m = -0.0185T_c + 3.5481$$

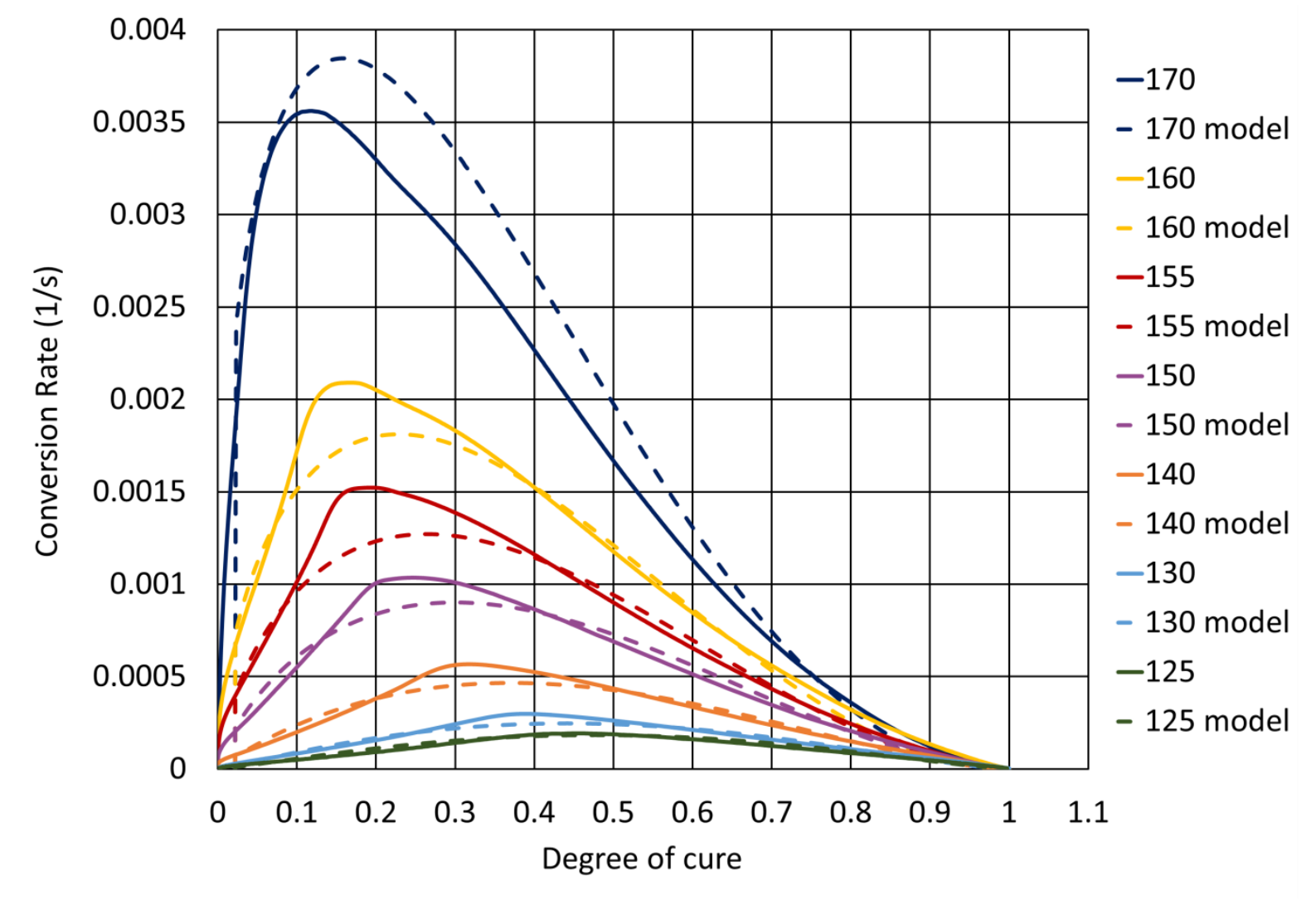
$$n = \begin{cases}0.182, & T < 60℃\\ 0.0183T_c - 0.9334, & T \geq 60℃\end{cases}$$

$$A^* = 2.81\ 1/s$$

$$E_a = 77.53\ kJ/mol$$

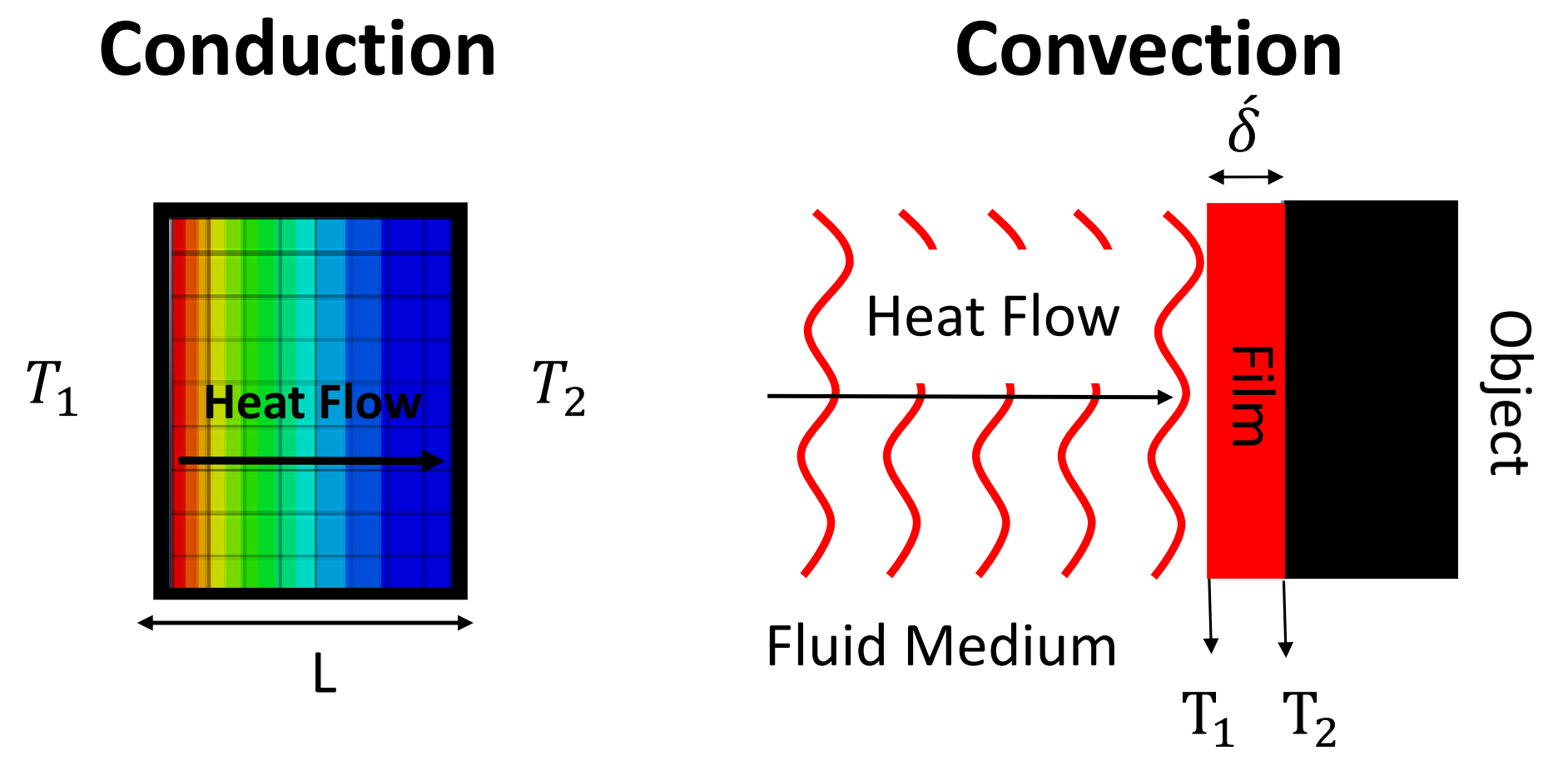
$$\frac{d\alpha}{dt} = 2.81 \times \exp\left(-\frac{77.53}{RT}\right) \times \alpha^{\begin{cases}0.182, & T<60℃\\ 0.0183T_c-0.9334, & T\geq 60℃\end{cases}} \times (1-\alpha)^{-0.0185T_c+3.5481}$$

$\alpha \geq 0.022$
$T \geq 125℃$



Experimental and numerical conversion rate vs. degree of cure

Heat Transfer Analysis

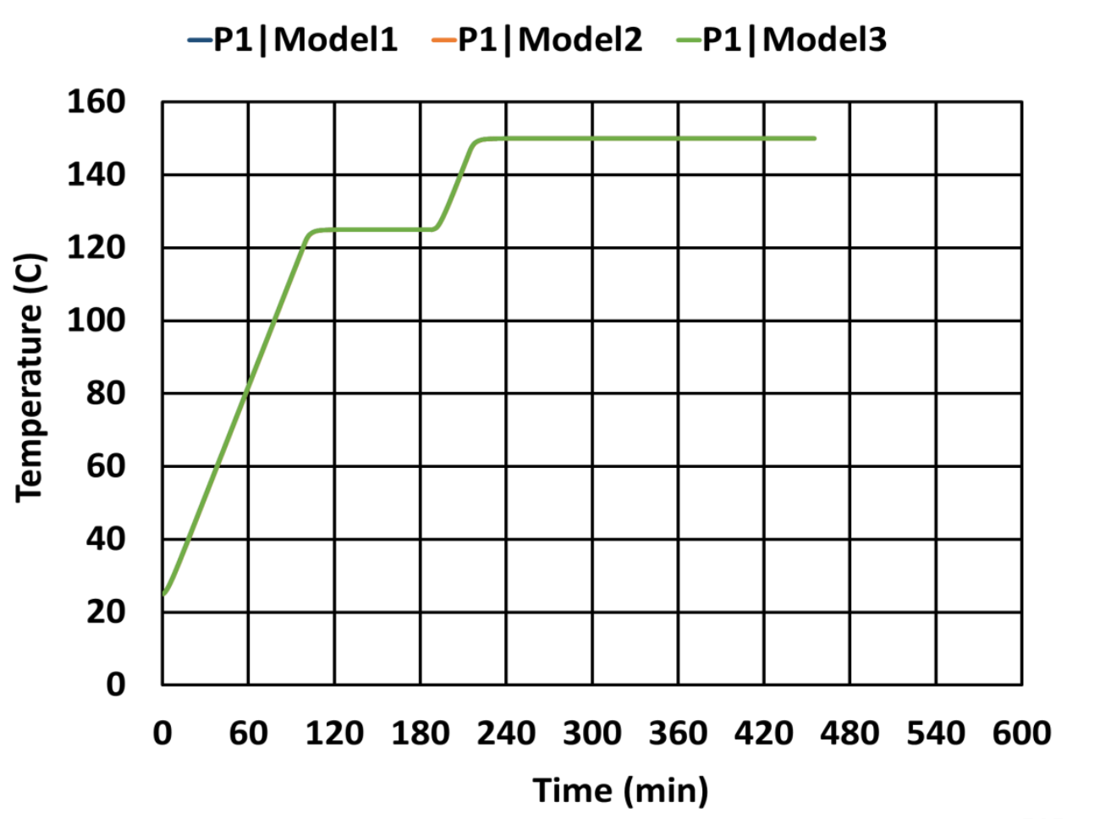


$$\underset{Conduction}{\dot{Q}} = \frac{k_{object}.A.(T_2 - T_1)}{L}$$ [3]

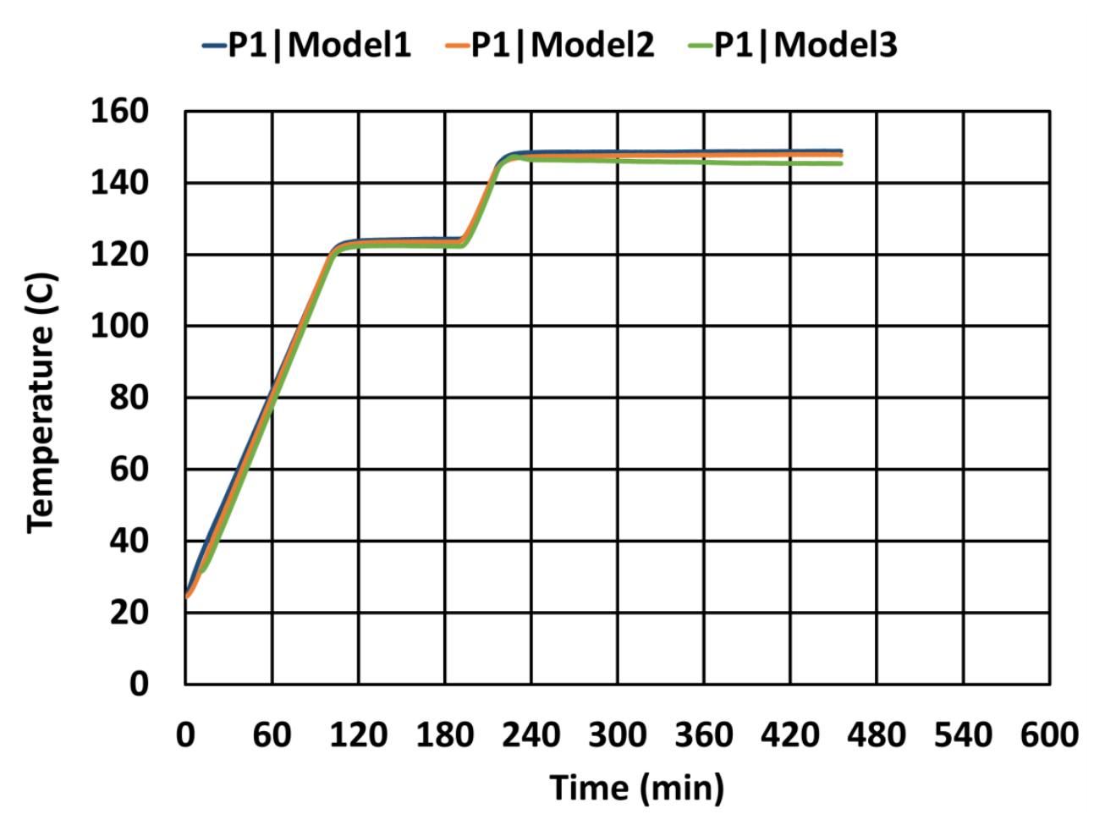
$$\underset{Convection}{\dot{Q}} = \frac{k_{fluid}.A.(T_2 - T_1)}{\dot{\delta}}$$ [3]

$$\frac{k_{fluid}}{\dot{\delta}} = h$$

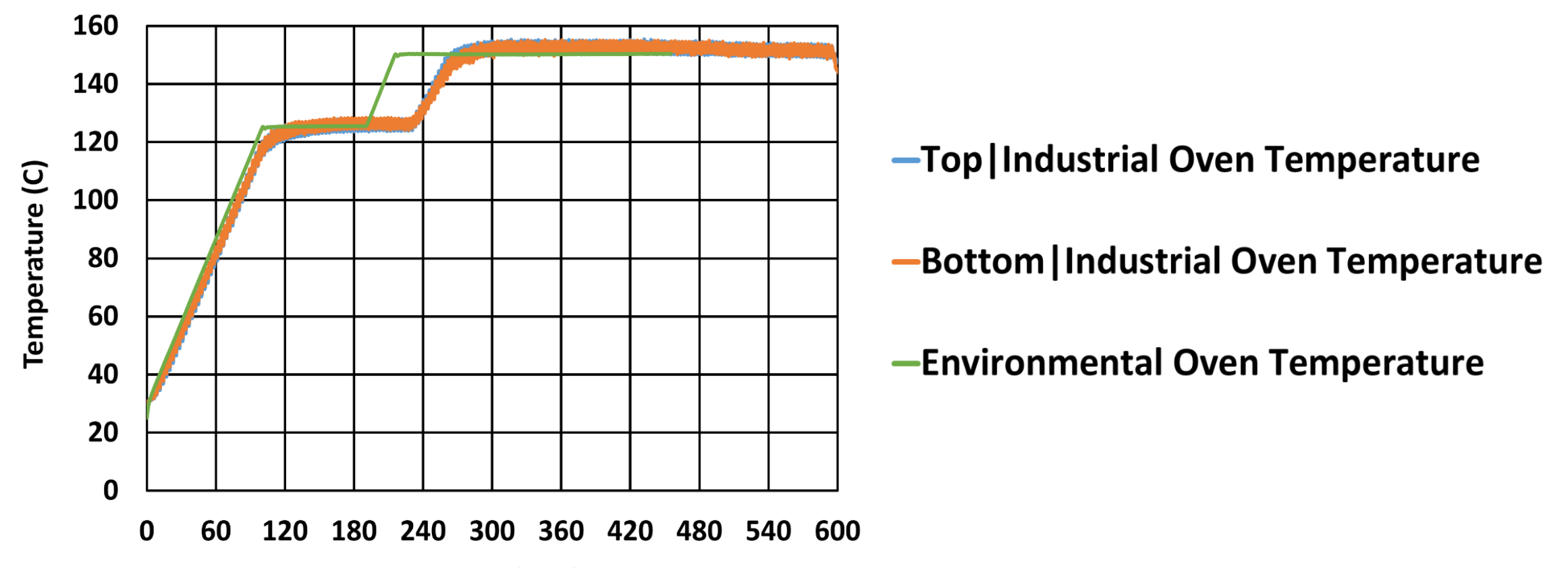
$\dot{Q}$: heat flow rate (J/s), k: thermal conductivity ($^W/_{m.K}$), T: Temperature (°C), L & $\dot{\delta}$: thickness (m)



Numerical results, using ABAQUS and h=35$\frac{W}{m^2.K}$



Experimental results, using environmental oven



Experimental results of oven temperature: environmental chamber vs. industrial oven

References

[1] Theodore L. Bergman, Introduction to Heat Transfer, 6th Edition, New York, NY: John Wiley & Sons, Jun 2011
[2] Q. Guo, Thermosets, Structure, Properties, and Applications, 2nd Edition, Woudhead Publishing, 14th November 2017.
[3] P. Z. Spakovszky, " Massachusetts Institute of Technology: MIT OpenCourseWare," Fall 2002. [Online]. Available: https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-050-thermal-energy-fall-2002/. [Accessed 25 June 2018].