HEAT TRANSFER IN COMPOSITES PROCESSING

CO-HOSTED BY:

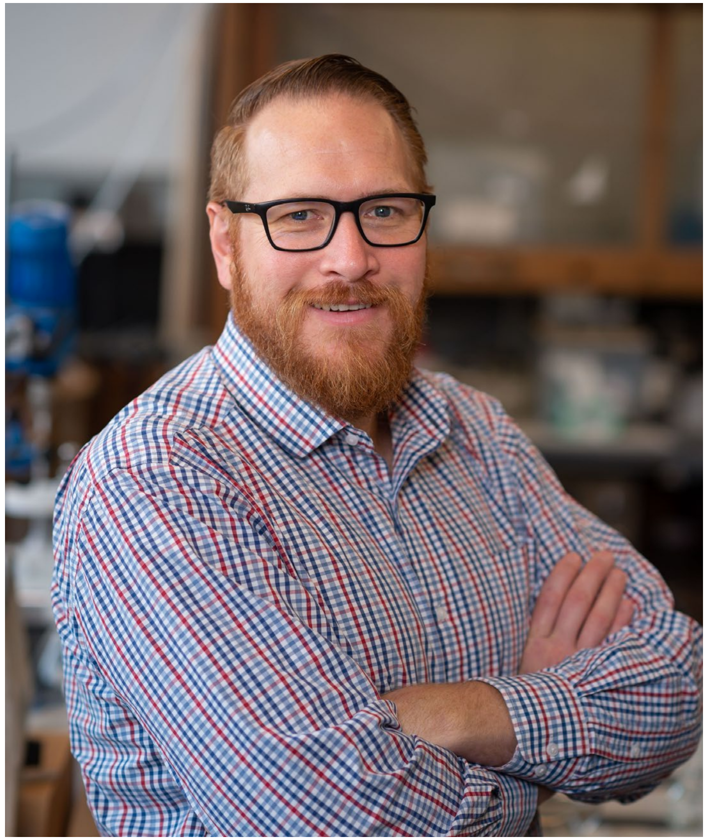
Composites Knowledge Network

sampe Canada

compositeskn.org

nasampe.org

YOUR HOSTS



Casey Keulen, Ph.D, P.Eng.
Assistant Professor of Teaching, University of British Columbia
Co-Director of Advanced Materials Manufacturing MEL Program, UBC
Director of Knowledge in Practice Centre, CKN

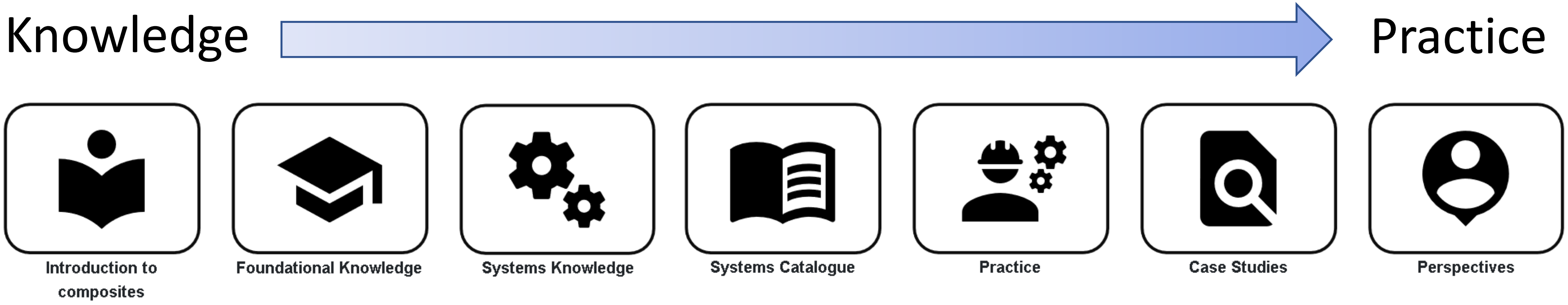
- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 15 years experience in industry and academia working on polymer matrix composites in aerospace, automotive, marine, energy, recreation and others
- Experience working with over 150 companies from SME to major international corporations
- Expertise in liquid composite moulding and thermal management

KNOWLEDGE IN PRACTICE CENTRE (KPC)

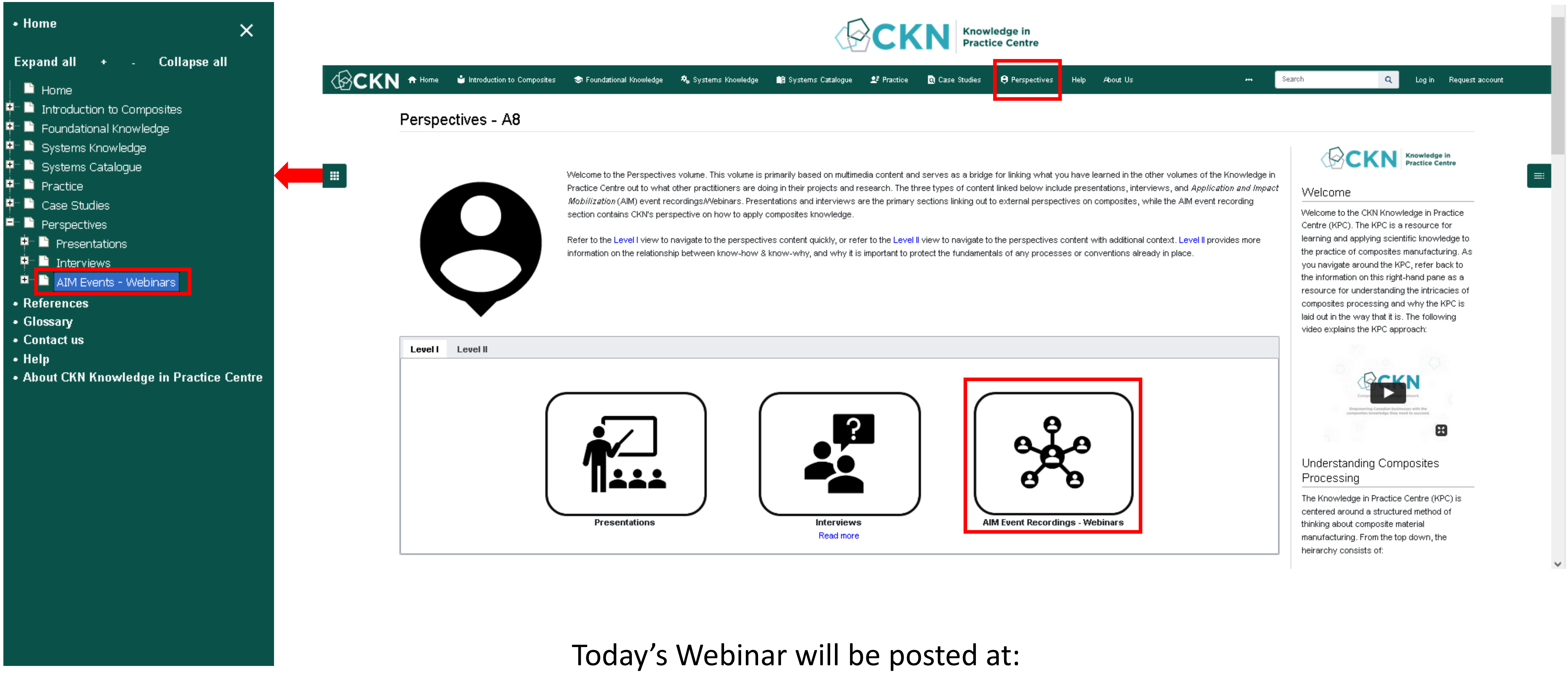
- A freely available online resource for composite materials engineering:

compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



PAST WEBINAR RECORDINGS AVAILABLE



Today's Webinar will be posted at:
https://compositeskn.org/KPC/A321

HOSTED BY: CKN Composites Knowledge Network

HOSTED BY: sampe Canada

TODAY'S TOPIC:

Heat Transfer in Composites Processing

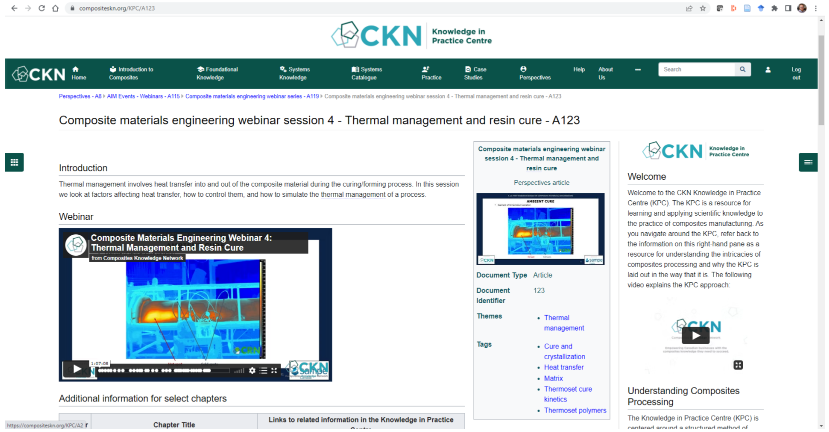
OUTLINE

- Introduction and learning objectives
- Heat transfer fundamentals
  - Convection
  - Conduction
  - Conservation of energy
  - Thermal mass
  - Thermal resistance
- Exothermic heat generated by composite
- Cure cycles and thermal lag
- Curing environments
- Tooling
- Simulation

INTRODUCTION

- **Learning objectives:**
  - Understand fundamentals of heat transfer
  - Understand the basics of heat transfer in a curing environment
  - Understand how tooling effects heat transfer
  - Understand how simulation can be used to model composite processes

- We've discussed thermal management in the past
  - https://compositeskn.org/KPC/A123 - for our thermal management webinar



HOSTED BY:
Composites Knowledge Network

HOSTED BY:
Canada

WHAT IS HEAT TRANSFER?

- *Heat transfer (or heat) is thermal energy in transit due to a temperature difference*[1]

Heat is energy, not to be mistaken with temperature (temperature is the measure of heat in a given material)

'in transit' implies that it is moving

A temperature difference is the driving mechanism

- Whenever there is a temperature difference, heat transfer must occur

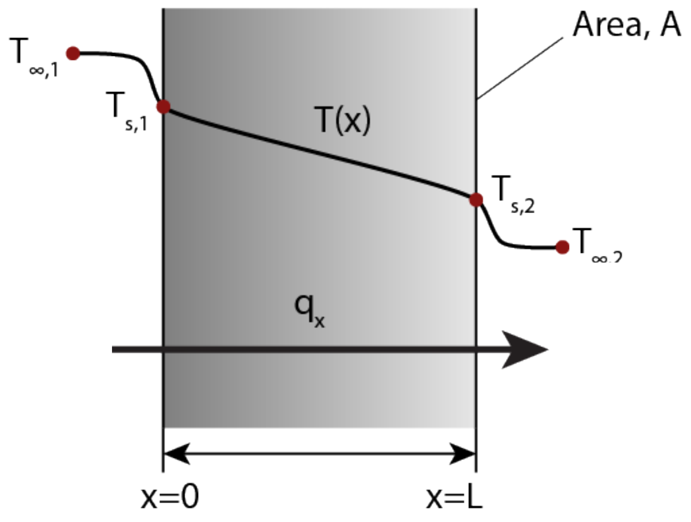
- Generally speaking, we are concerned with rates that heat transfer occurs

[1] Incropera, F., DeWitt, D., Fundamentals of Heat and Mass Transfer, John Wiley and Sons, 2002

MODES OF HEAT TRANSFER

- Heat transfer through a solid is ***conduction***
- Recall Fourier's law:

$$q_x'' = k\frac{\Delta T}{L}$$



- Where q_x'' is heat flux [W/m^2]
- k is thermal conductivity [W/m^{2}K]
- ΔT is the temperature difference [K]
- L is the distance between the temperature difference [m]
- The heat rate in [W] can be found by:

$$q_x = q_x'' A$$

[1] Incropera, F., DeWitt, D., Fundamentals of Heat and Mass Transfer, John Wiley and Sons, 2002

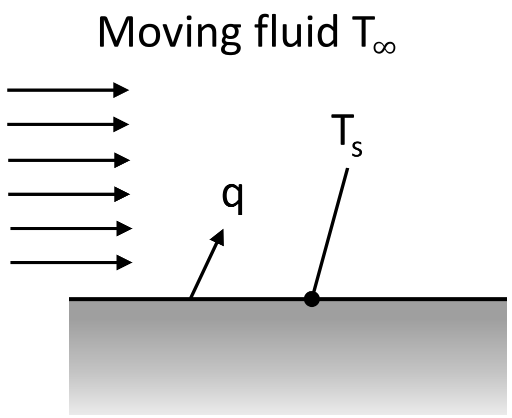
MODES OF HEAT TRANSFER

- Heat transfer through a fluid to a solid is ***convection***

- Recall Newton's law of cooling:

$$q'' = h\Delta T$$

- Where q'' is convective heat flux [W/m^2]
- h is the heat transfer coefficient, HTC [W/m^{2}K]
- ΔT is the temperature difference [K] between T_s and T_∞



[1] Incropera, F., DeWitt, D., Fundamentals of Heat and Mass Transfer, John Wiley and Sons, 2002

MODES OF HEAT TRANSFER

- ***Radiation***: conduction and convection are the dominant heat transfer modes, radiation is generally negligible in composites manufacturing
- ***First law of thermodynamics:*** *Conservation of energy*

$$E_{in} + E_g - E_{out} = \Delta E_{st}$$

Energy going in

Energy generated

Energy going out

Energy stored

[1] Incropera, F., DeWitt, D., Fundamentals of Heat and Mass Transfer, John Wiley and Sons, 2002

MODES OF HEAT TRANSFER

- **Radiation:** conduction and convection are the dominant heat transfer modes, radiation is generally negligible in composites manufacturing

- **First law of thermodynamics:** *Conservation of energy*

$$E_{in} + E_g - E_{out} = \Delta E_{st}$$

Energy going in

Heat from environment (hot air, or tool)

Energy generated

Exothermic energy from cure reaction

Energy going out

Exothermic energy removed from the material

Energy stored

Which leads to temperature change

[1] Incropera, F., DeWitt, D., Fundamentals of Heat and Mass Transfer, John Wiley and Sons, 2002

SPECIFIC HEAT CAPACITY

- Heat capacity is a material property that represents a material's ability to absorb heat:

$$c_p = \frac{1}{m} \cdot \frac{dQ}{dT}$$

- Quantity of energy required to raise the temperature of a material by one degree

THERMAL MASS

- Thermal mass represents the inertia against temperature fluctuation:

$$Thermal\ Mass = mc_p$$

Mass

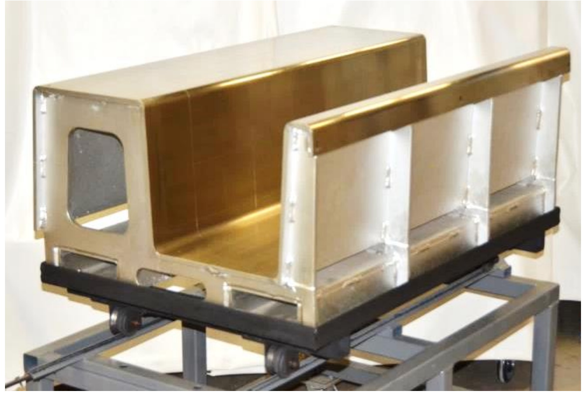
Specific heat capacity: Amount of heat to raise the temperature of 1 kg mass by 1 degree

- Thermal mass depends on both the mass of an object (e.g. tool) and also the material (e.g. steel tool vs. composite tool)

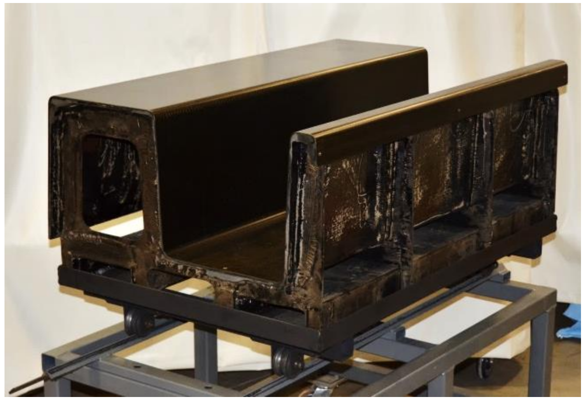
THERMAL MASS EXAMPLE

- Consider three tools with exact geometries but with different materials.

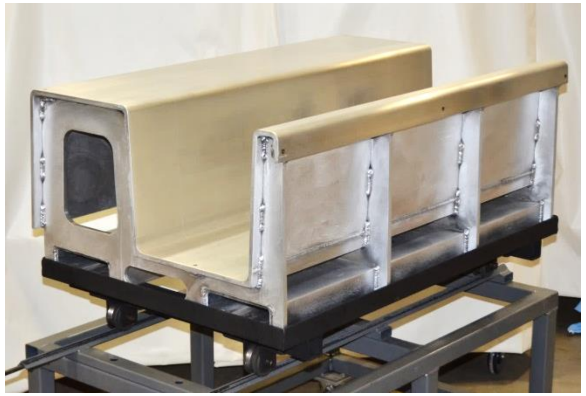
Invar



Composite



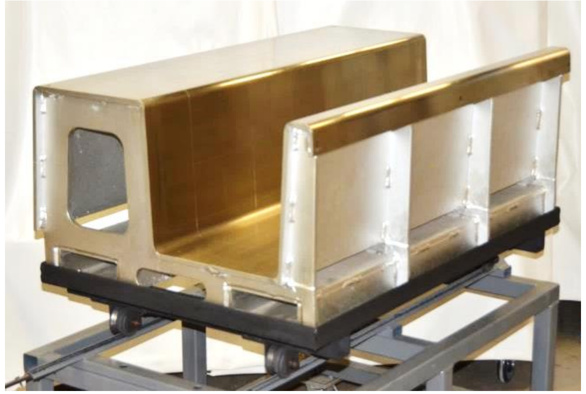
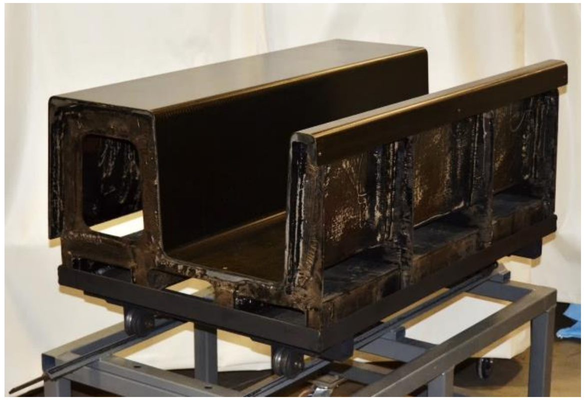
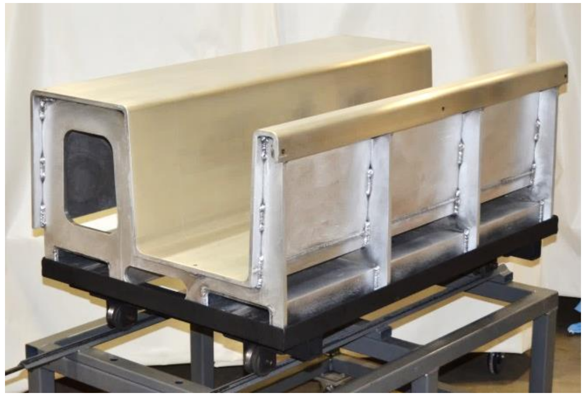
Aluminum



	Invar	Composite	Aluminum
Cp (J/kg-K)	515	870	896

THERMAL MASS EXAMPLE

- Consider three tools with exact geometries but with different materials.

	Invar	Composite	Aluminum
			
Cp (J/kg-K)	515	870	896
m (kg)	400	80	135
m.Cp(kJ/K)	206 Large Thermal Mass	70	121

- Due to the high thermal mass, more energy is required to heat-up the Invar tool
- For the typical range of manufacturing parameters, it takes longer to heat-up Invar
- Aluminum or Composite are usually faster to heat-up

TOOLING MATERIALS

Tooling Materials	Cost	Durability	Conductivity	Thermal Mass	Weight	CTE
Composite						
Steel						
Aluminum						
Invar						

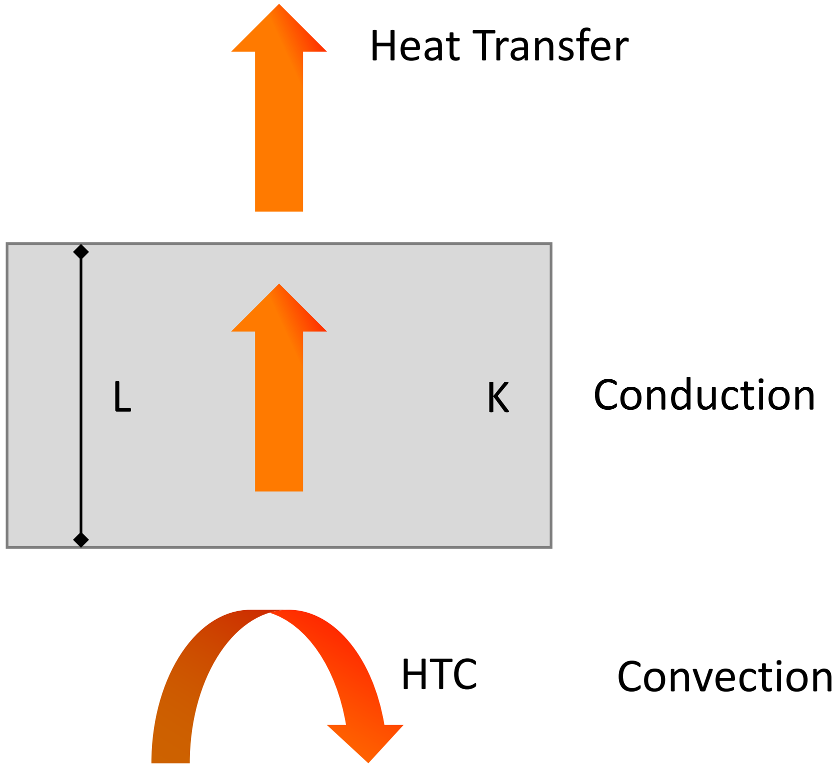
Bad	Average	Good

THERMAL RESISTANCE

- Thermal resistance is a measurement of resistance to heat flow
- It is defined for convection as (1/HTC) and conduction as (L/K)
- Larger the thermal resistance, longer it takes to transfer the heat

Conductive Thermal Resistance:
L/K (Length/Conductivity)

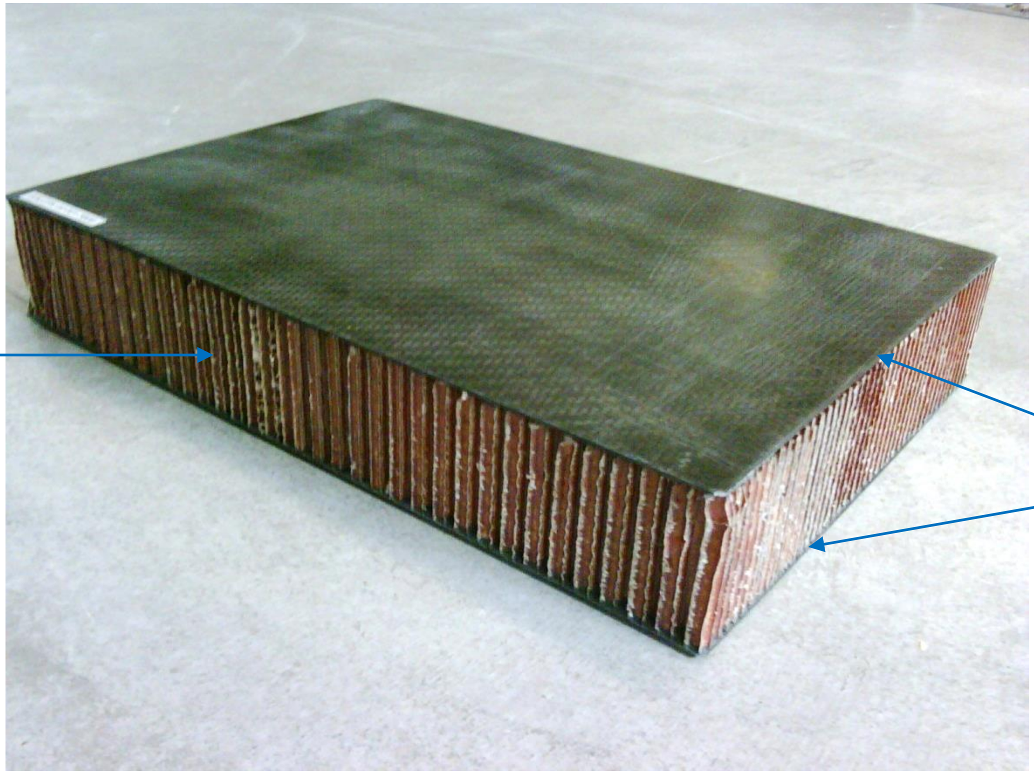
Convective Thermal Resistance:
1/HTC



EXAMPLE OF THERMAL RESISTANCE

Curing of a composite sandwich panel on a tool is discussed here:

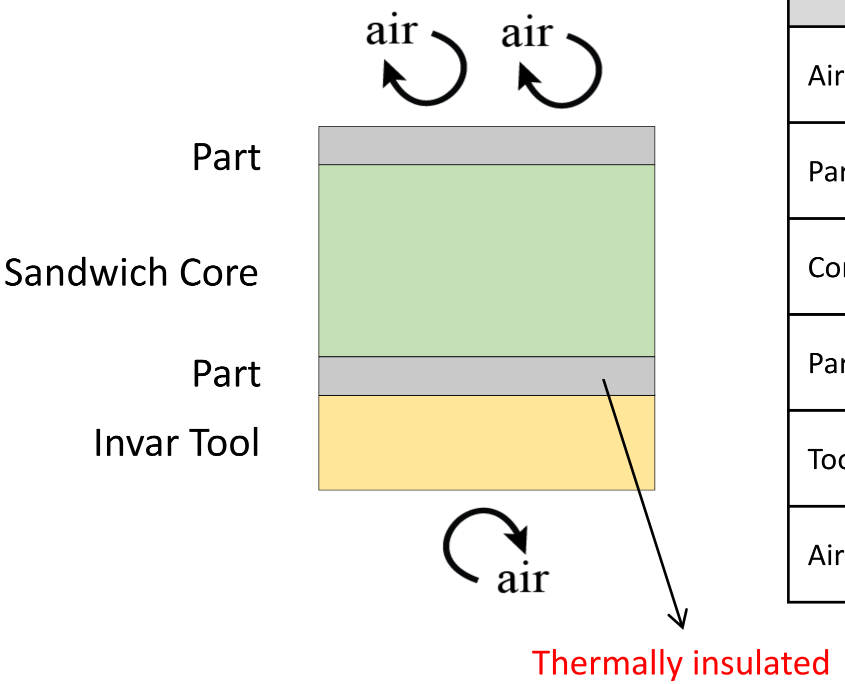
Thick honeycomb core



Thin composite facesheets

EXAMPLE OF THERMAL RESISTANCE

- Consider a composite sandwich panel on an Invar tool with the following thicknesses and HTC values (high airflow on top, low airflow at the bottom):



	HTC (W/m^2K)	K (W/mK)	Thickness (mm)	Thermal Resistance ($10^{-3} \cdot m^2K/W$)
Air	100			1/HTC = 10
Part		0.7	4	L/K = 6
Core		0.09	20	L/K = 222
Part		0.7	4	L/K = 6
Tool		11	10	L/K = 1
Air	10			1/HTC = 100

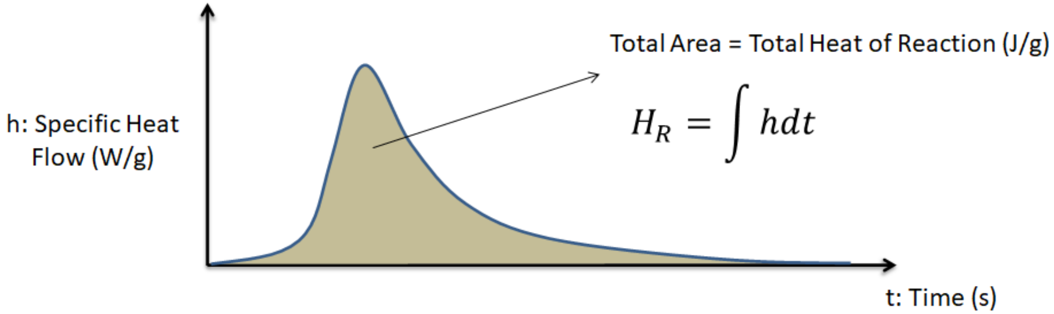
High Thermal Resistance

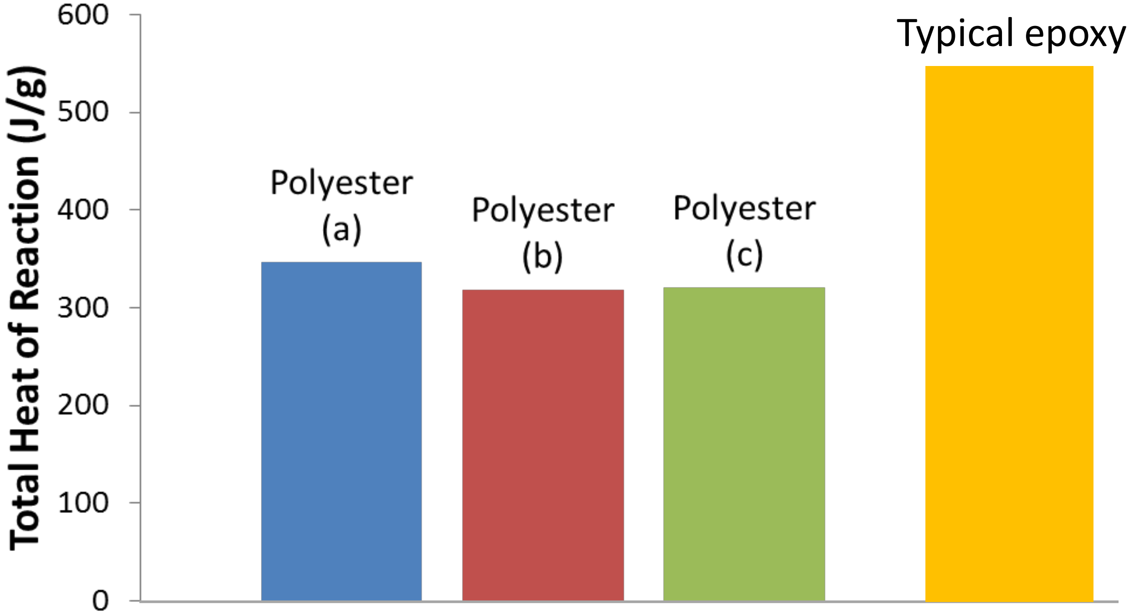
High Thermal Resistance

- The bottom composite part is insulated by the sandwich core on one side and low HTC on the other side
- Could cause heat-damage during the exothermic reaction or prevent the part to fully cure

HEAT OF REACTION AND CURE KINETICS

- Polymerization of thermoset resins is an ***exothermic reaction*** and heat is generated during the curing process
- A thermoset resin has the potential to release a certain amount of energy while curing, referred to as the total heat of reaction, H_R (unit of J/g)





HEAT OF REACTION AND CURE KINETICS

- Cure kinetics equations are obtained by data fitting the experimental results

Example: $$\frac{d\alpha}{dt} = Ae^{-\Delta E/RT}\alpha^m(1-\alpha^n)$$

m, n, R, A, ΔE: constants

T: temperature

Measured experimentally

Data fitting

- The rate of resin heat generation ($\dot{Q}_r$) is calculated from the cure kinetics equations and the total mass of the resin

Resin density

$$\dot{Q}_r = \frac{d\alpha}{dt} H_R V_r \rho_r$$

Resin volume fraction

CURE CYCLES

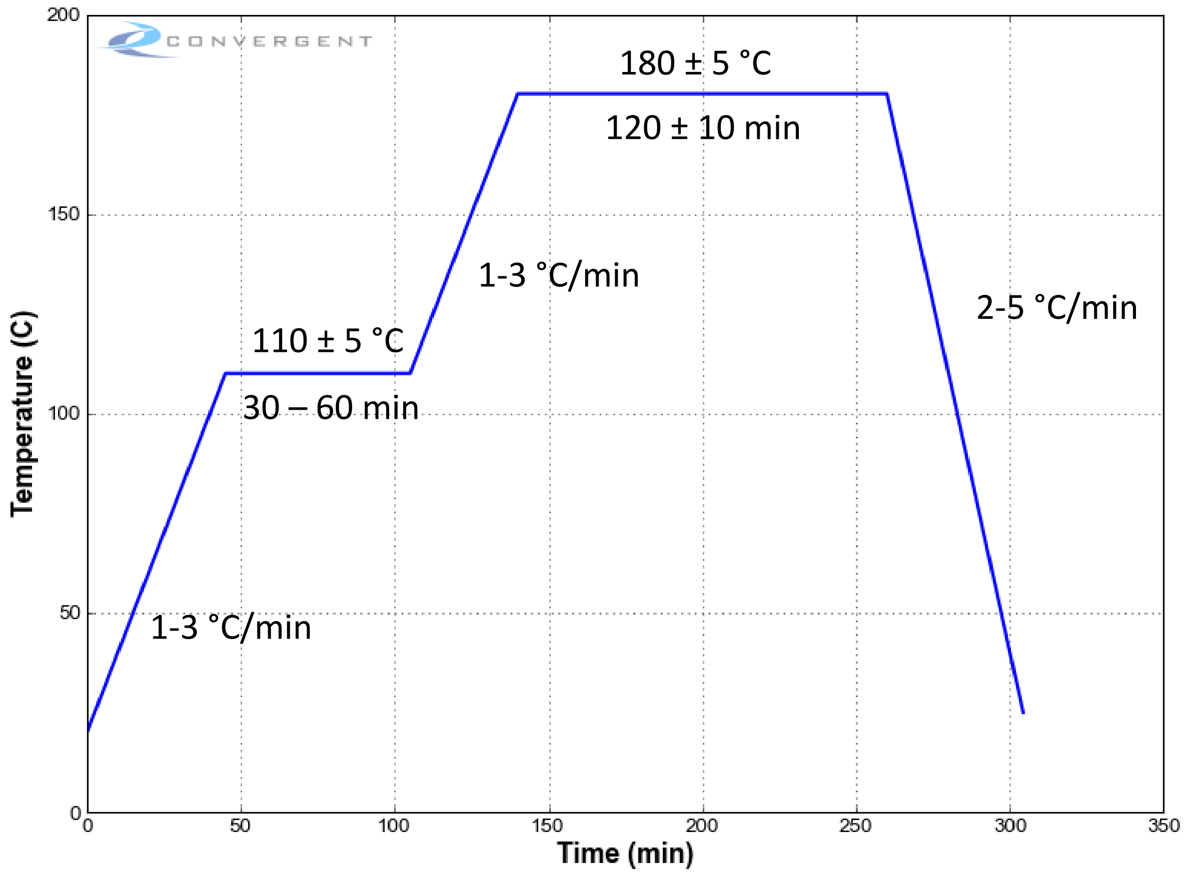
- Resin manufacturers usually provide recommend cure cycles (i.e. recipes)
- Here is a manufacturer's recommended temperature cure cycle (MRCC) for the 8552 Epoxy:

Manufacturer: Hexcel

Resin: 8552 Epoxy

Typical Application: Aerospace

Autoclave Manufacturing



CURE CYCLES

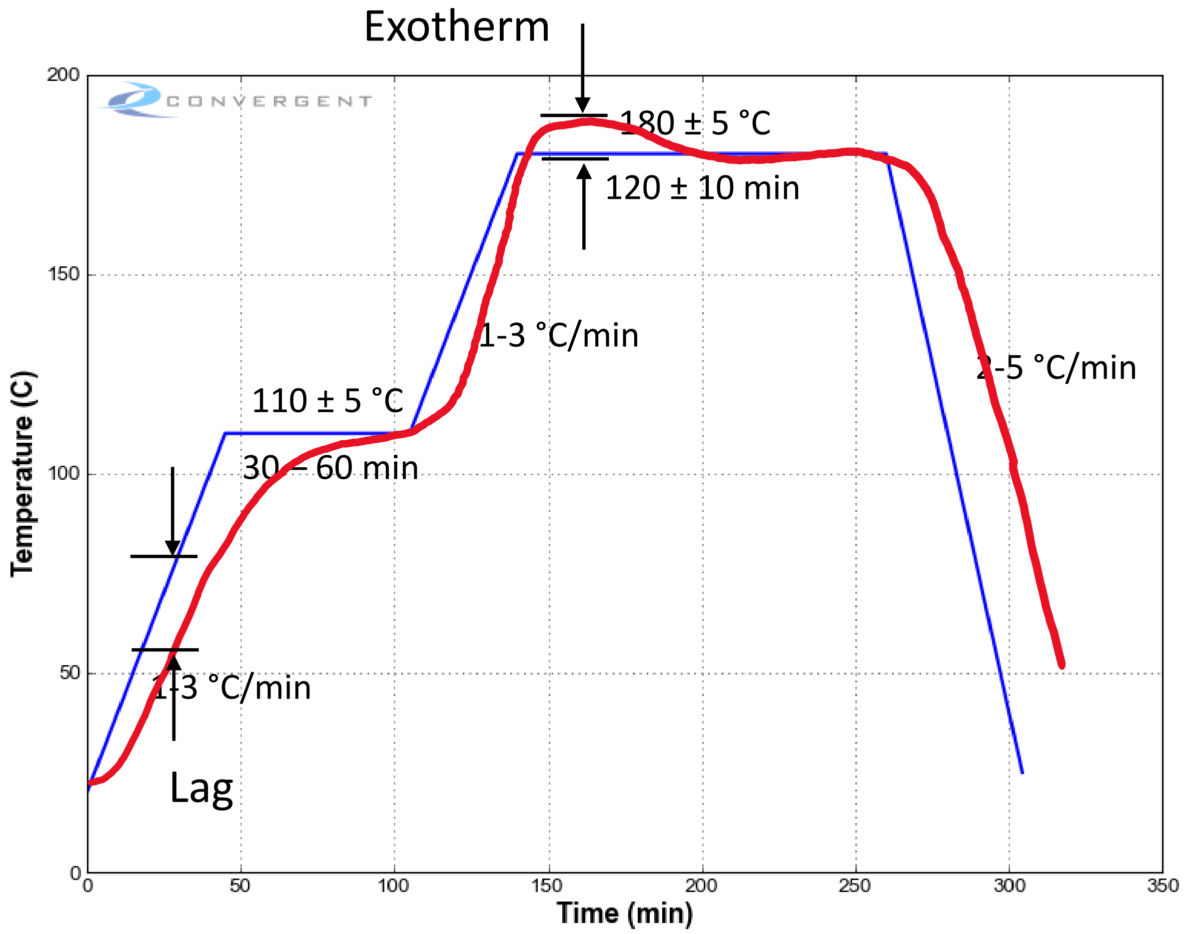
- Resin manufacturers usually provide recommend cure cycles (i.e. recipes)
- Here is a manufacturer's recommended temperature cure cycle (MRCC) for the 8552 Epoxy:

Manufacturer: Hexcel

Resin: 8552 Epoxy

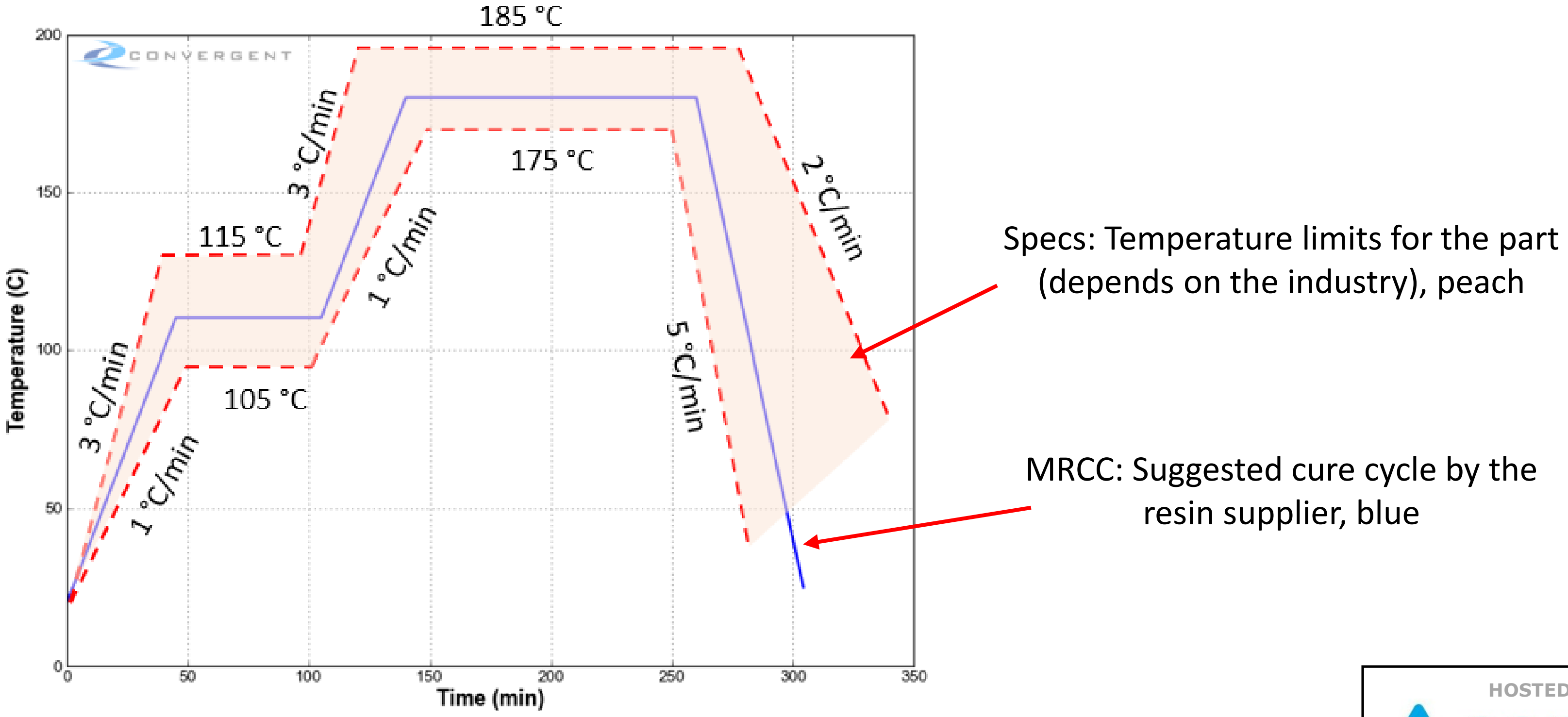
Typical Application: Aerospace

Autoclave Manufacturing



CURE CYCLES VS. SPECS

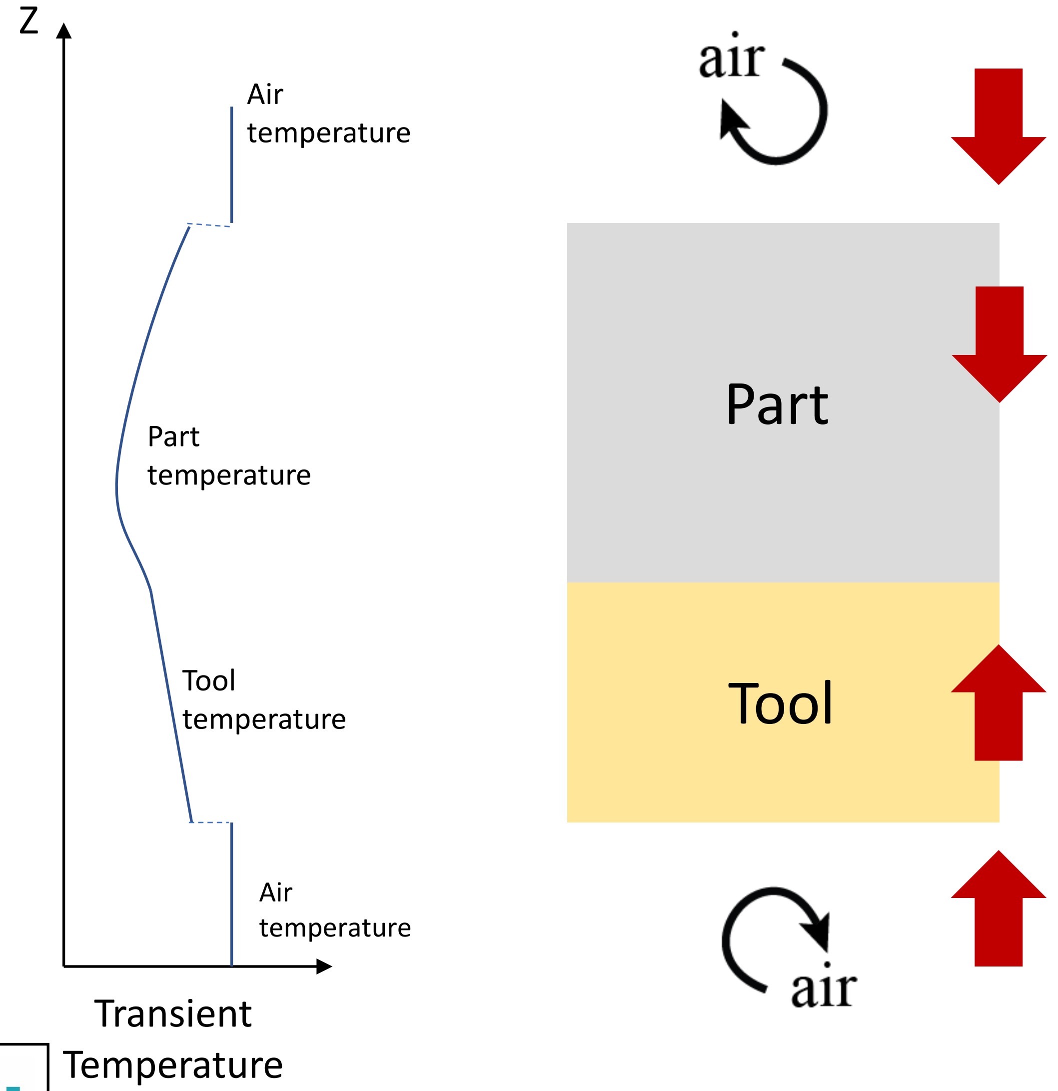
- Cure cycles are the intended temperature and pressure cycles for oven/autoclave (air temperature) or heated moulds (tool temperature)
- Temperature limits for the part are defined by specs (industry dependent)
- For a part to be approved the temperature of every point in the part should be within the defined bound during the manufacturing process



HOSTED BY: CKN Composites Knowledge Network

HOSTED BY: sampe Canada

1D THERMO-CHEMICAL ANALYSIS: HEAT-UP STEP



Rate of heat transfer by convection

$$\dot{Q} = h.A.\Delta T$$

Energy balance:

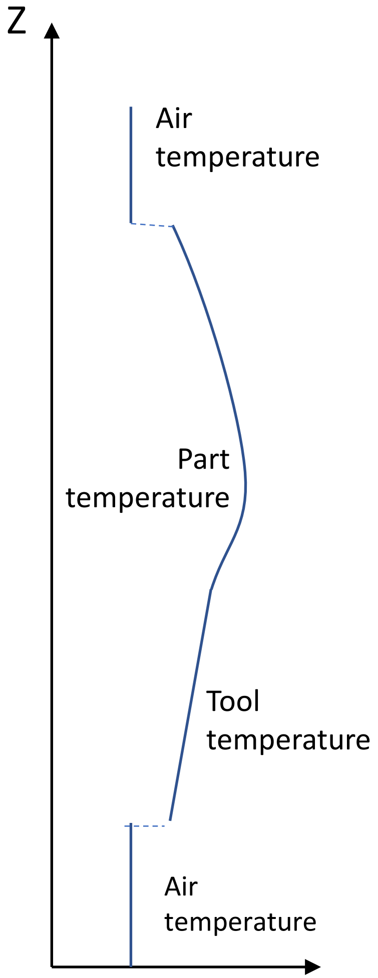
$$\frac{\partial}{\partial t}\left(\rho C_P T\right) = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right)$$

rate of increase of heat = rate of heat addition by conduction

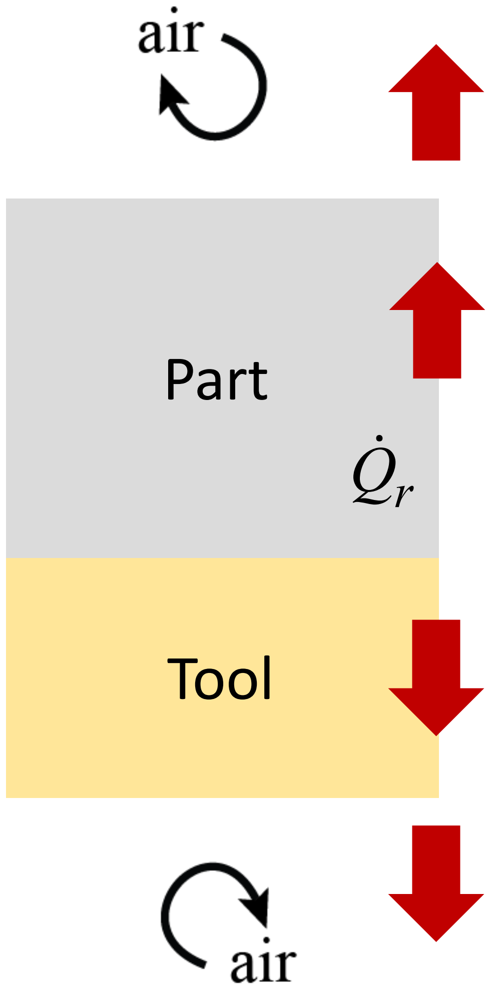
Rate of heat transfer by convection

$$\dot{Q} = h.A.\Delta T$$

1D THERMO-CHEMICAL ANALYSIS: EXOTHERMIC STEP



Transient Temperature



Rate of heat transfer by convection

$$\dot{Q} = h.A.\Delta T$$

Energy balance:

$$\frac{\partial}{\partial t}\left(\rho C_P T\right) = \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{Q}_r$$

rate of increase of heat = rate of heat addition by conduction + rate of resin heat generation

Rate of heat transfer by convection

$$\dot{Q} = h.A.\Delta T$$

THERMAL LAG IN THE TOOL

- While heating the tool in an oven or autoclave, the thermal lag of the mould can be estimated using the following equation:

$$\Delta T = -\frac{\dot{T}L^2}{a}\left(\frac{1}{2}+\frac{1}{Bi}\right) \qquad Bi = \frac{hL}{k} \qquad a = \frac{k}{\rho c_p}$$

$\dot{T}$: heating rate

L: half of the tool thickness

a: tool diffusivity

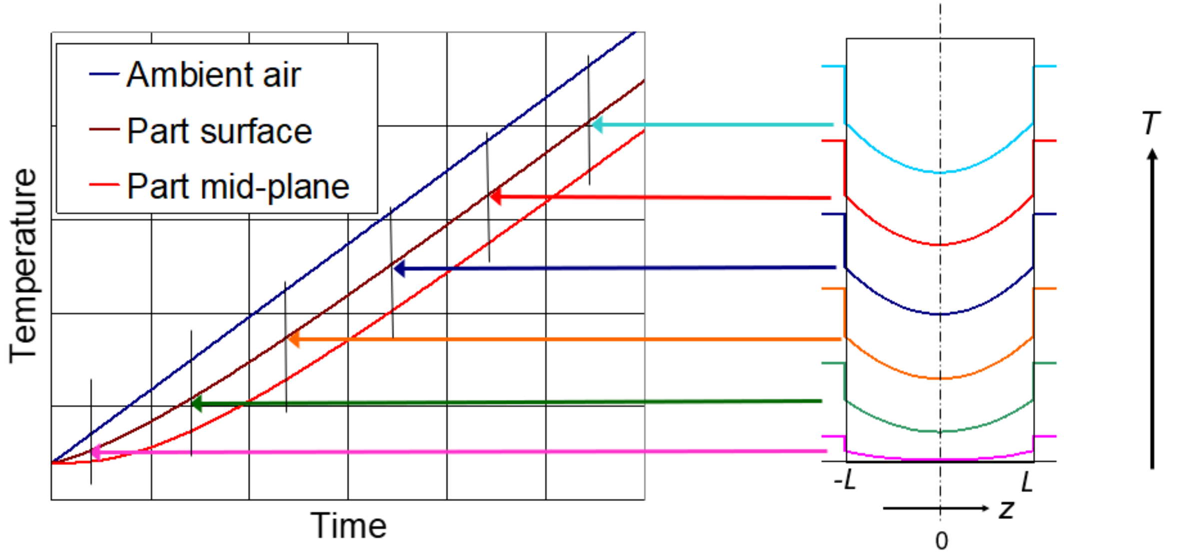
Bi: Biot number

h: heat transfer coefficient

k: tool thermal conductivity

C_p: tool specific heat capacity

ρ: tool density



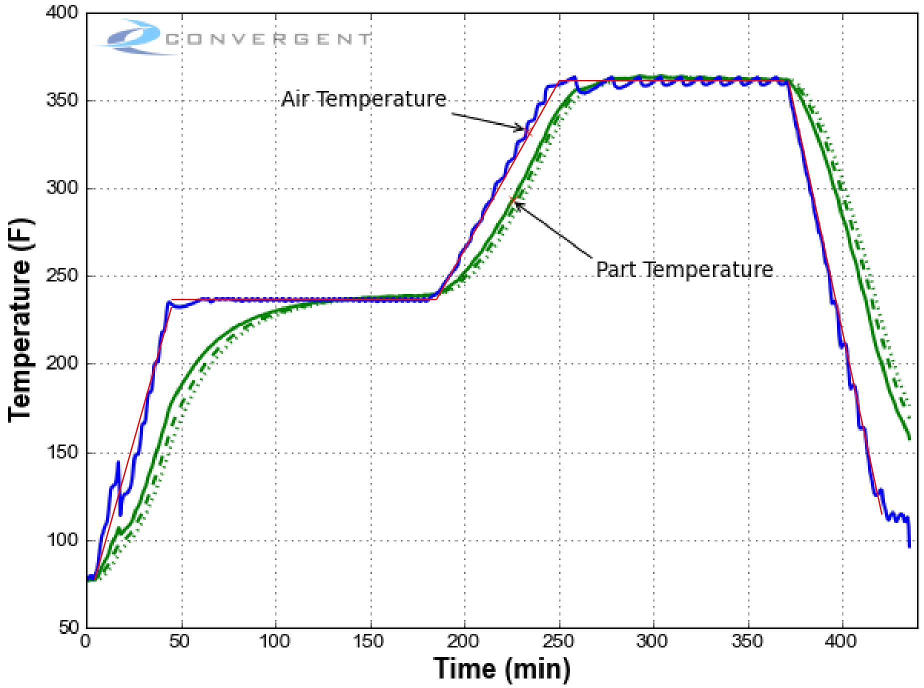
CONTROLLING HEAT TRANSFER: AUTOCLAVE

- Essentially, an autoclave can be thought of as a:
    - Pressurized oven
    - Heated pressure vessel
- Used to consolidate and cure composite

Boeing 777X Autoclave, Everett Washington

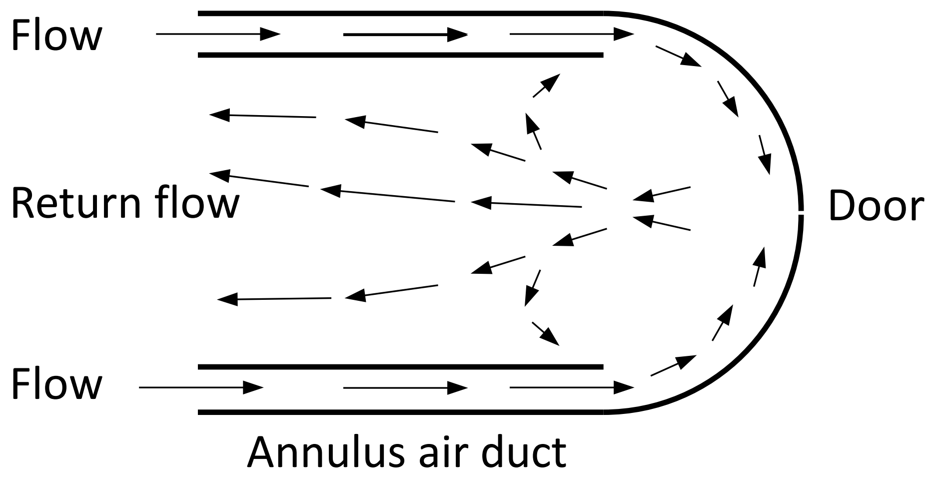
CONTROLLING HEAT TRANSFER: AUTOCLAVE

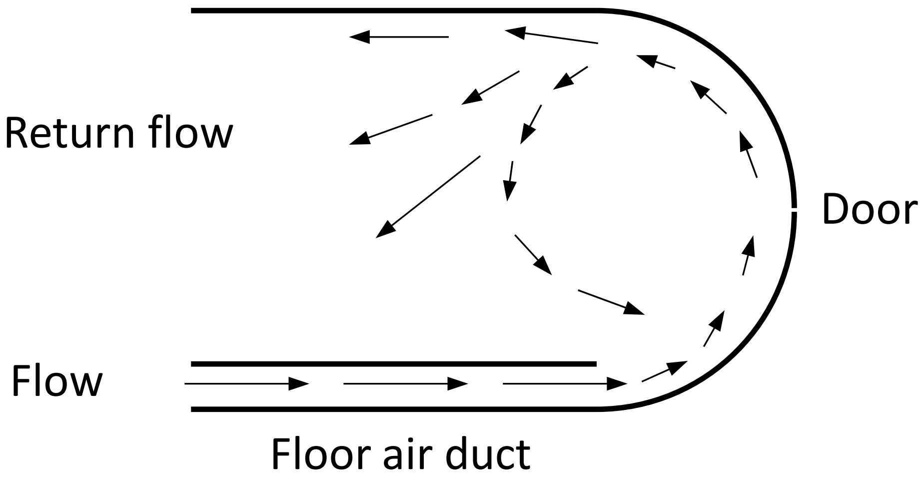
- For ovens and autoclaves, the actual part temperature will deviate from the applied air temperature due to the heat transfer conditions between the air and the part, tool, vacuum bag assembly, etc.



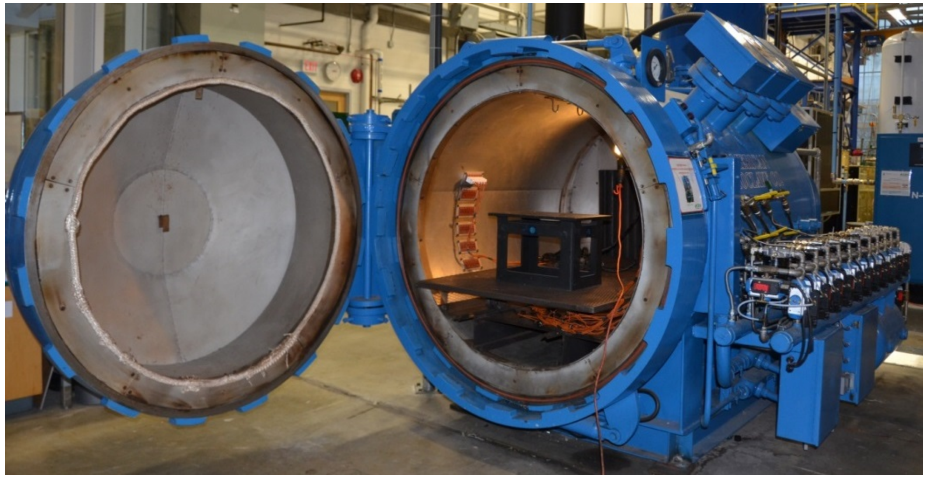
AUTOCLAVE AIRFLOW

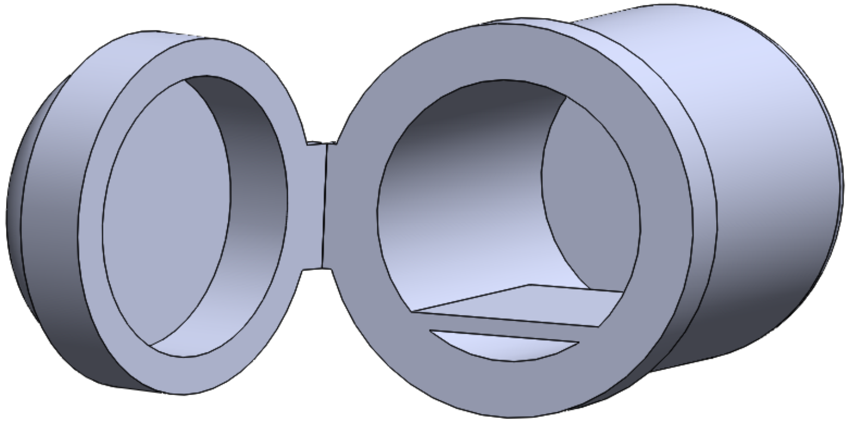
- Two common airflow patterns inside an autoclave

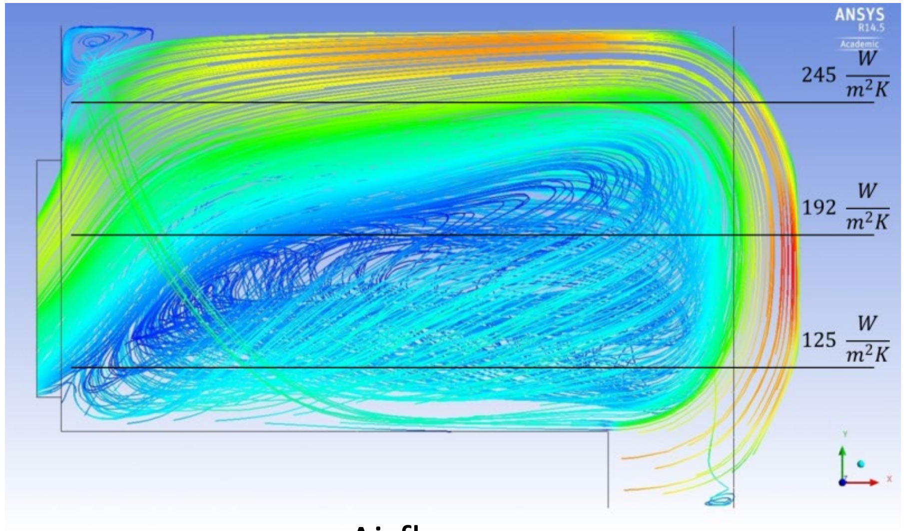




AUTOCLAVE AIRFLOW



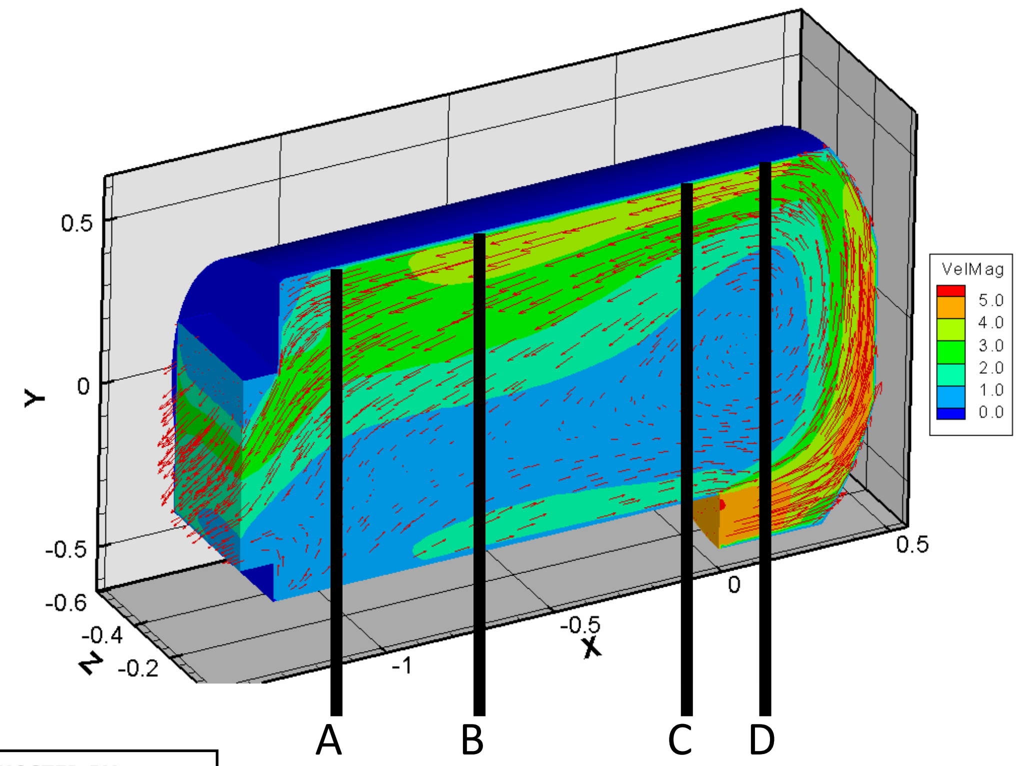


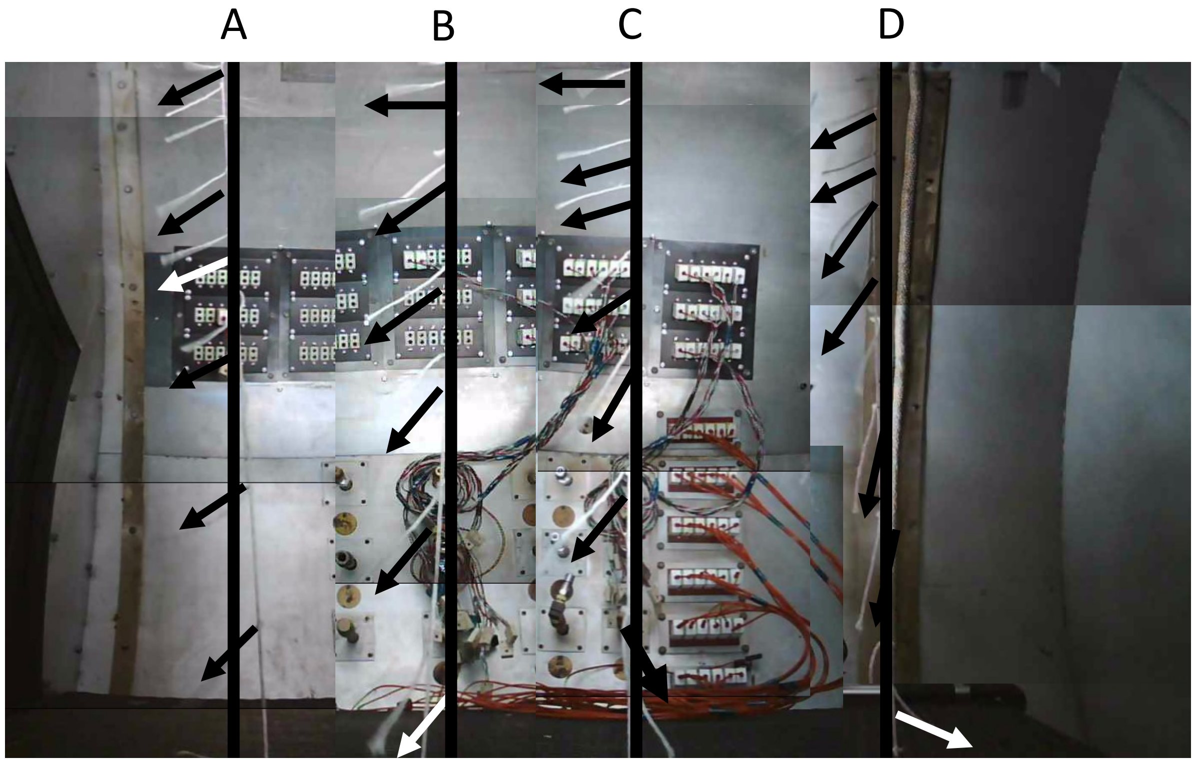


Airflow

AUTOCLAVE AIRFLOW

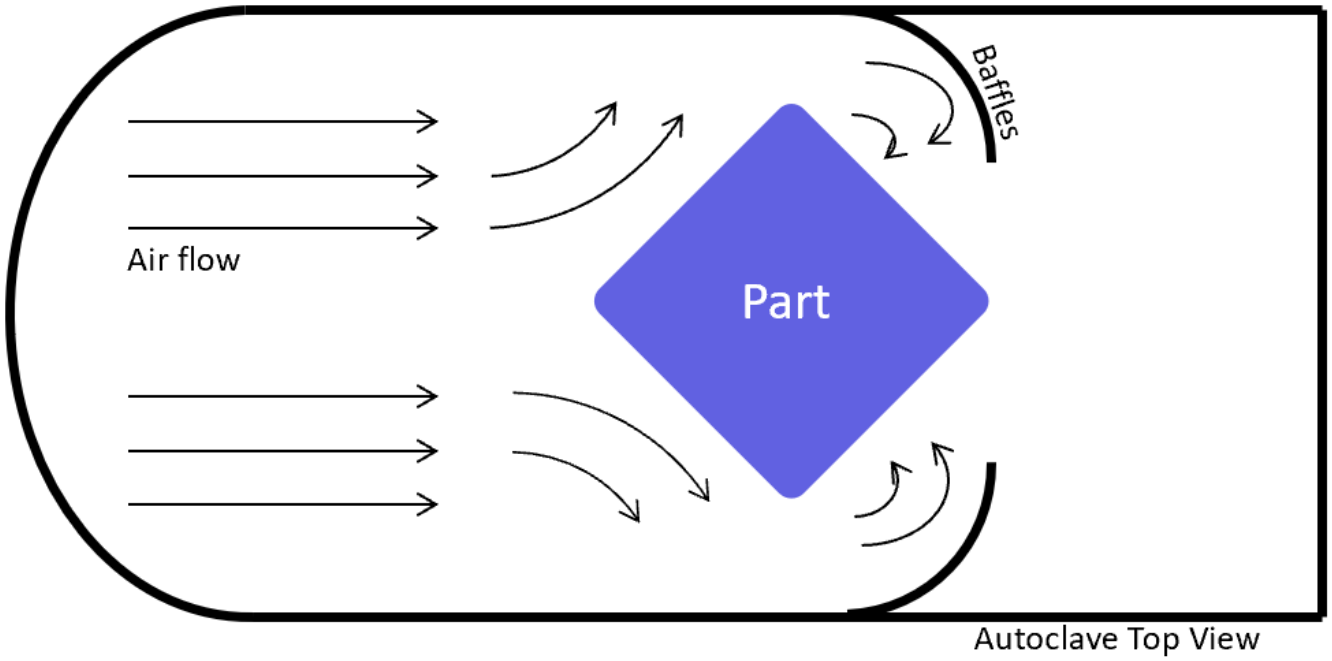
- Heating systems are not necessarily uniform and heat transfer can depend on the distribution of air flow within the heating chamber (autoclave or oven)





AUTOCLAVE AIRFLOW

- Baffles can be used in the autoclave or oven to orient and direct air flow to all locations around the part
- If baffles are used, they need to be consistent with every part produced and should be controlled with process documents

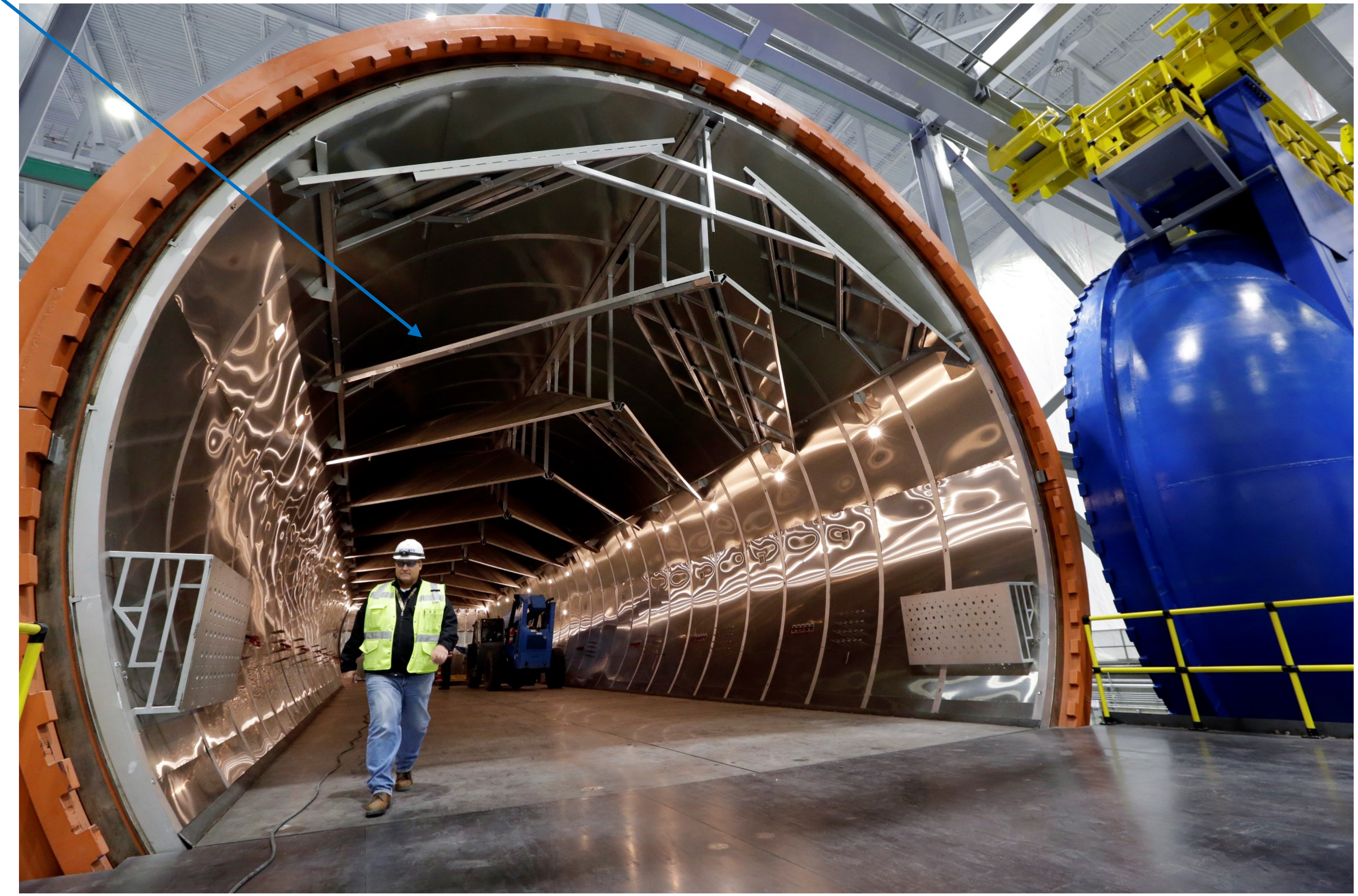


AUTOCLAVE AIRFLOW

Diffusers (Baffles)

AUTOCLAVE AIRFLOW

Diffusers (Baffles)



HEAT TRANSFER COEFFICIENT

- The convective heat transfer coefficient (HTC) quantifies the rate of heat transfer between the surrounding fluid and the object surface temperature through the boundary layer

- The HTC is dependent on:
- Air Velocity
- Air Pressure
- Air Temperature
- Laminar or turbulent flow
- Surface orientation
- Surface geometry

Density

Newton's law of cooling:

$$q'' = \underbrace{h}_{\text{HTC}}\Delta T$$

- HTC values will vary from surface to surface and location to location within the autoclave

ESTIMATING HEAT TRANSFER COEFFICIENTS

Estimating HTC's

- For an ideal gas with constant velocity and fully developed turbulent flow, the effect of temperature and pressure on the HTC can be estimated as:

$$h \propto \left(\frac{P}{T}\right)^{\frac{4}{5}}$$

- For a typical Autoclave:

Flow Condition	HTC $\left[{}^{W}/_{m^2 \cdot K}\right]$
Stagnant Gas	5
Low	10
Medium	30
High	60+
Impinging	100+

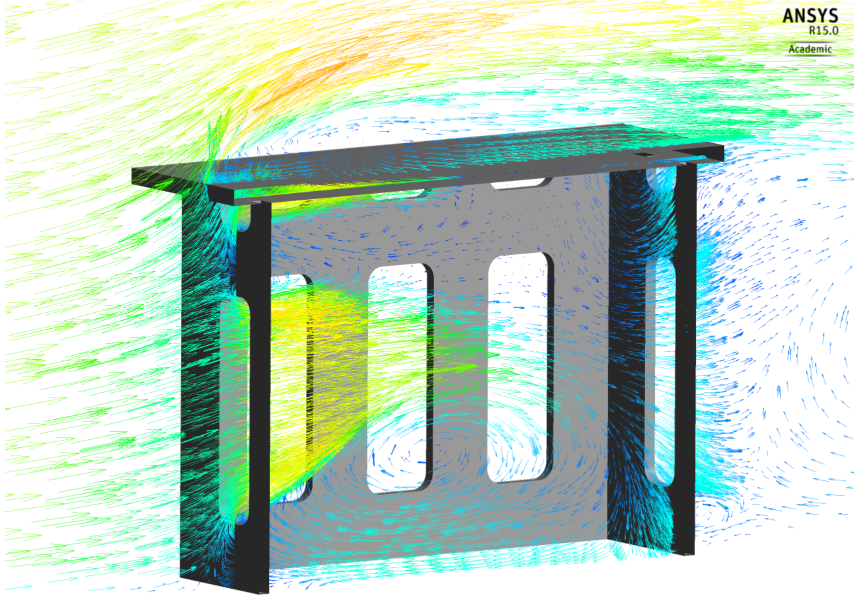
- Consider calibrating estimates against known temperatures or performing a sensitivity analysis

CHARACTERIZING HEAT TRANSFER COEFFICIENTS

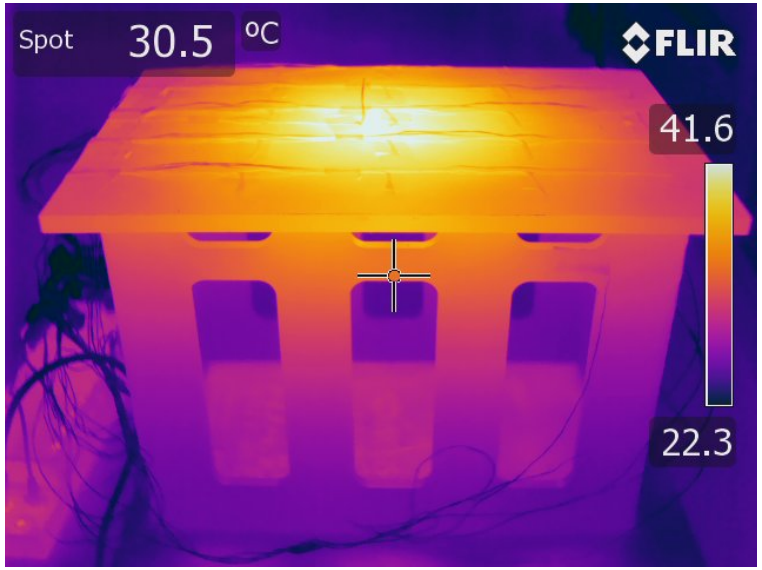
	Advantages	Disadvantages
Anemometers	•Measures actual velocity values	•Non-directional •Noisy results (turbulence) •Expensive, difficult to position •Local – need to know where
Calorimeters	•Inexpensive •Provides representative HTC values	•Time consuming data reduction •Non-directional •Length scale dependency (real HTC may be different) •Local - need to know where
CFD	•Shows velocity magnitude and direction •All areas can be evaluated •Parametric evaluation	•Model may lack realistic detail •Time consuming, expensive •Requires skilled personnel •Must be validated experimentally
Instrumented Part	•Provides actual HTC	•Accuracy limited by number of TCs •Time consuming data reduction •Autoclave load or part geometry changes require new test •Non-directional •Local - need to know where
Video	•Inexpensive •Intuitive to analyze •Large areas can easily be monitored	•Qualitative •Limited to ambient temperature and pressure

EFFECTS OF TOOL SUB-STRUCTURE ON HTC

- Overall, the tool sub-structure has the following effects:
  - Blocks the airflow to reduce the HTCs
  - Increases the surface area for heat transfer through convection
  - Increases the heat transfer through conduction and acts as a heat sink
  - Increases the thermal mass of the tool to increase the heat-up time
- Sub-structures may create hot or cold spots depending on the airflow, surface area, thermal mass and conductivity



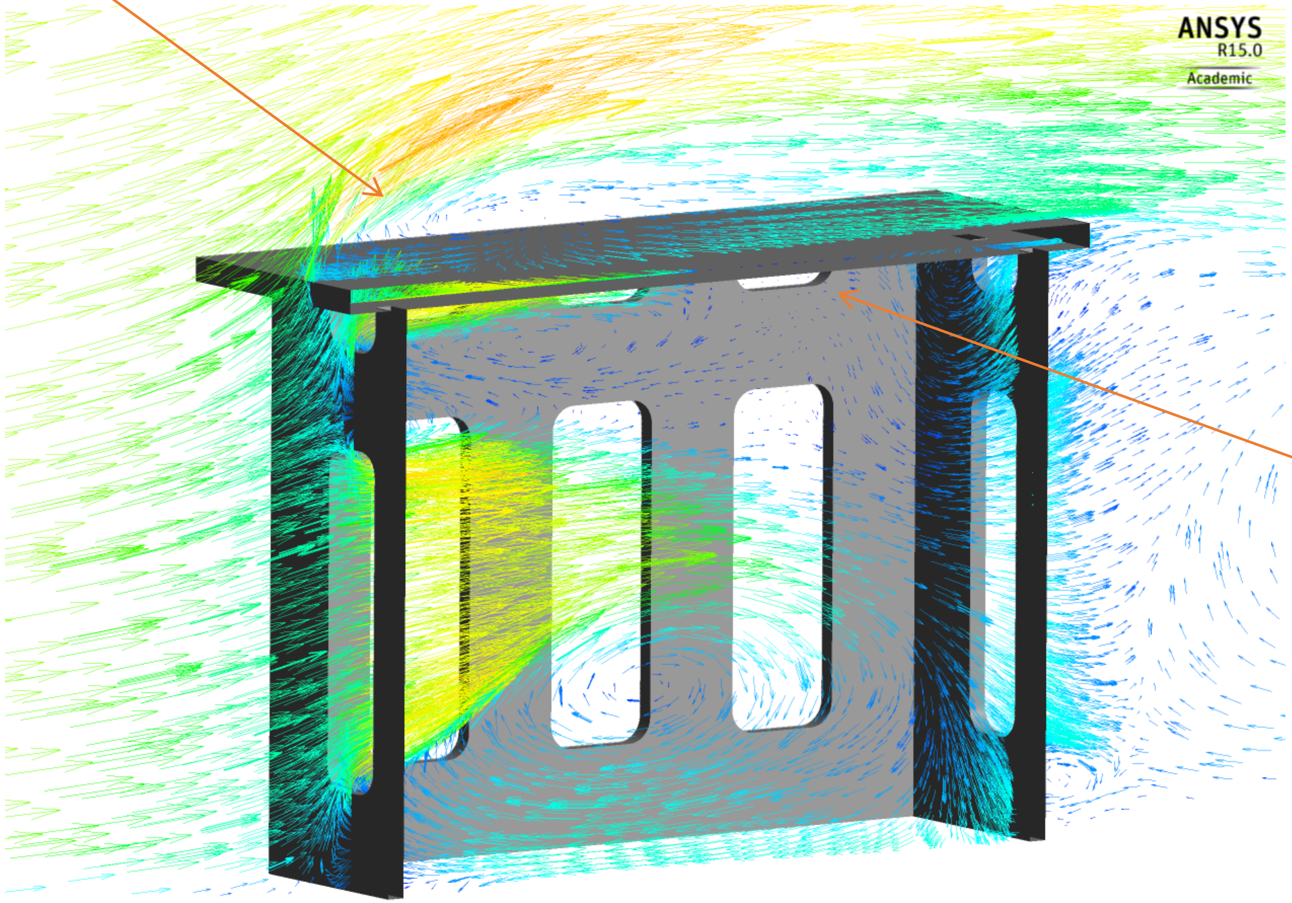
Reduced air velocity



Hot and cold spots

EFFECTS OF TOOL SUB-STRUCTURE ON HTC

Good airflow: High HTC



Bad airflow:
Low HTC

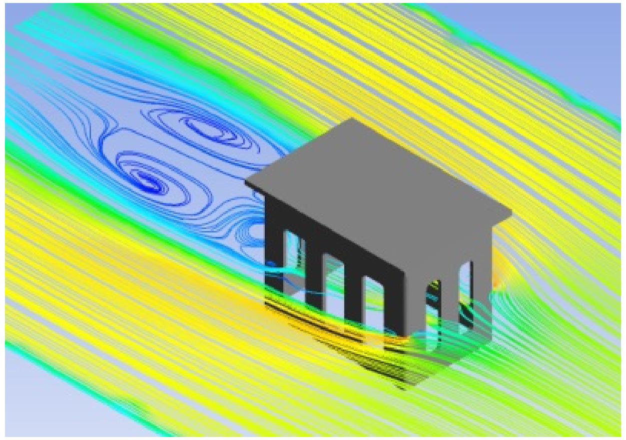
CFD analysis on half of a steel tool

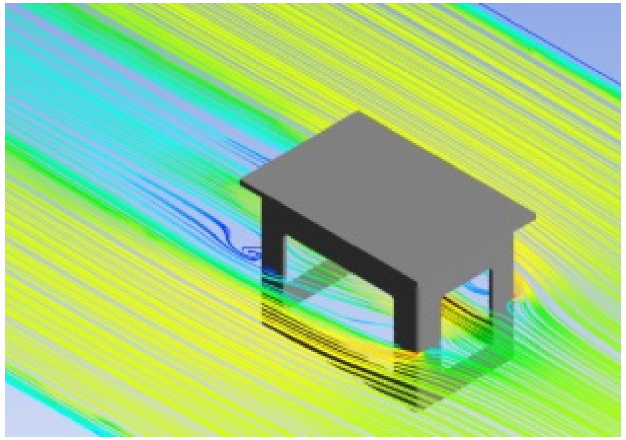
EFFECTS OF TOOL SUB-STRUCTURE ON HTC

Closed sub-structure

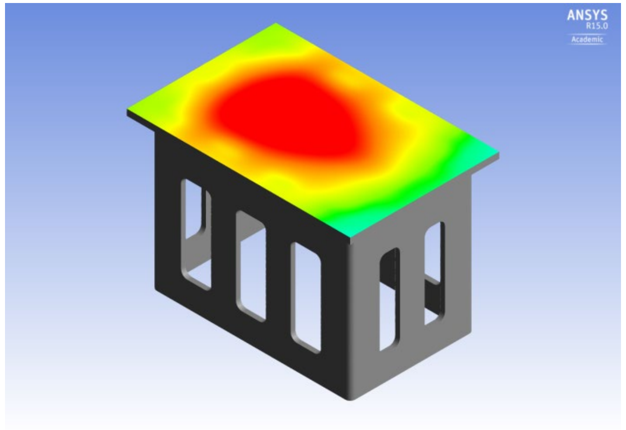
Open sub-structure

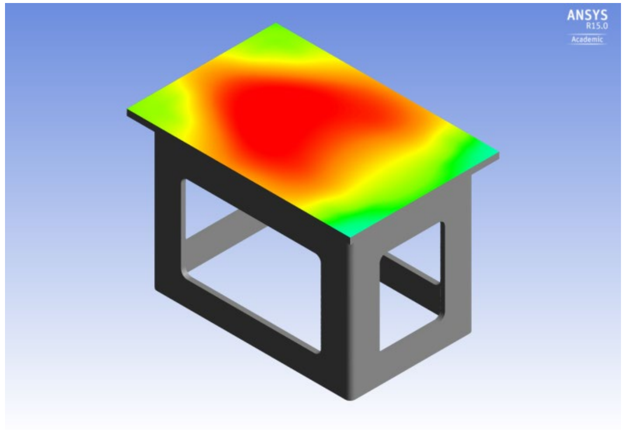
Airflow





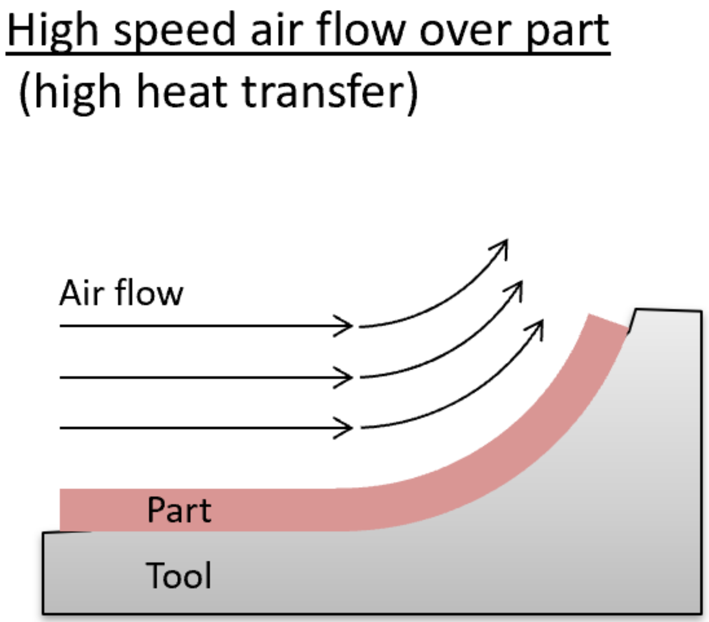
Temperature variation

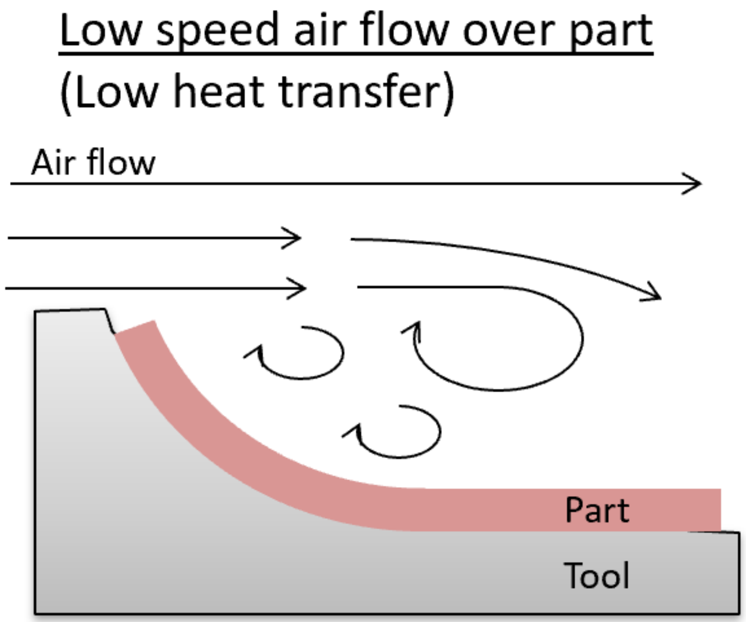




EFFECTS OF TOOL ORIENTATION SUB-STRUCTURE ON HTC

- Changing the orientation of a part within an autoclave or oven can affect the heat transfer conditions and result in under cured parts
- Placing multiple parts in an autoclave can affect the airflow over adjacent parts





EFFECTS OF TOOL ORIENTATION SUB-STRUCTURE ON HTC

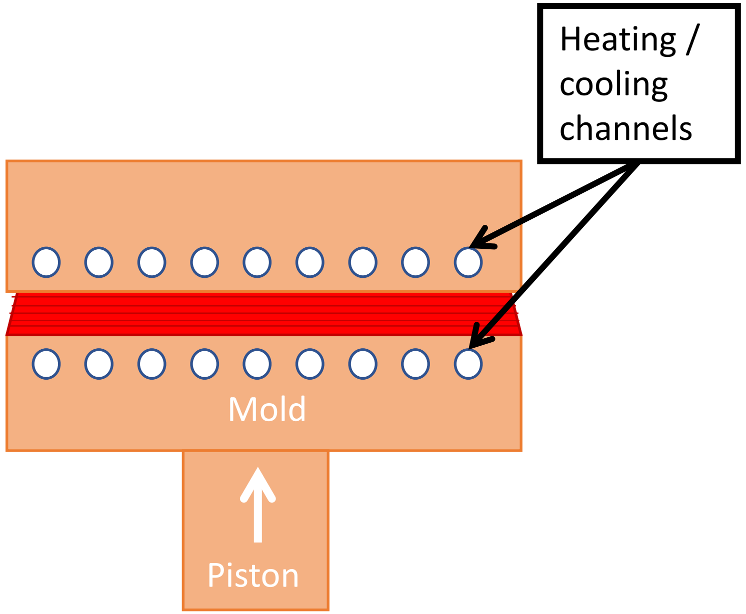
OVEN

- Non-pressurized chamber with temperature control
  - Results in lower density air -> lower HTC vs autoclave
- Variety of sizes and designs
- High quality ovens will circulate air and provide improved heat transfer

- **Advantages:**
  - High temperature cure
  - Possible to process large or irregularly shaped parts
  - More cost effective than autoclave
- **Limitations:**
  - Can be large and expensive
  - Maximum 1 atm. pressure with vacuum bag
  - Poor circulation can lead to uneven heat transfer to the part

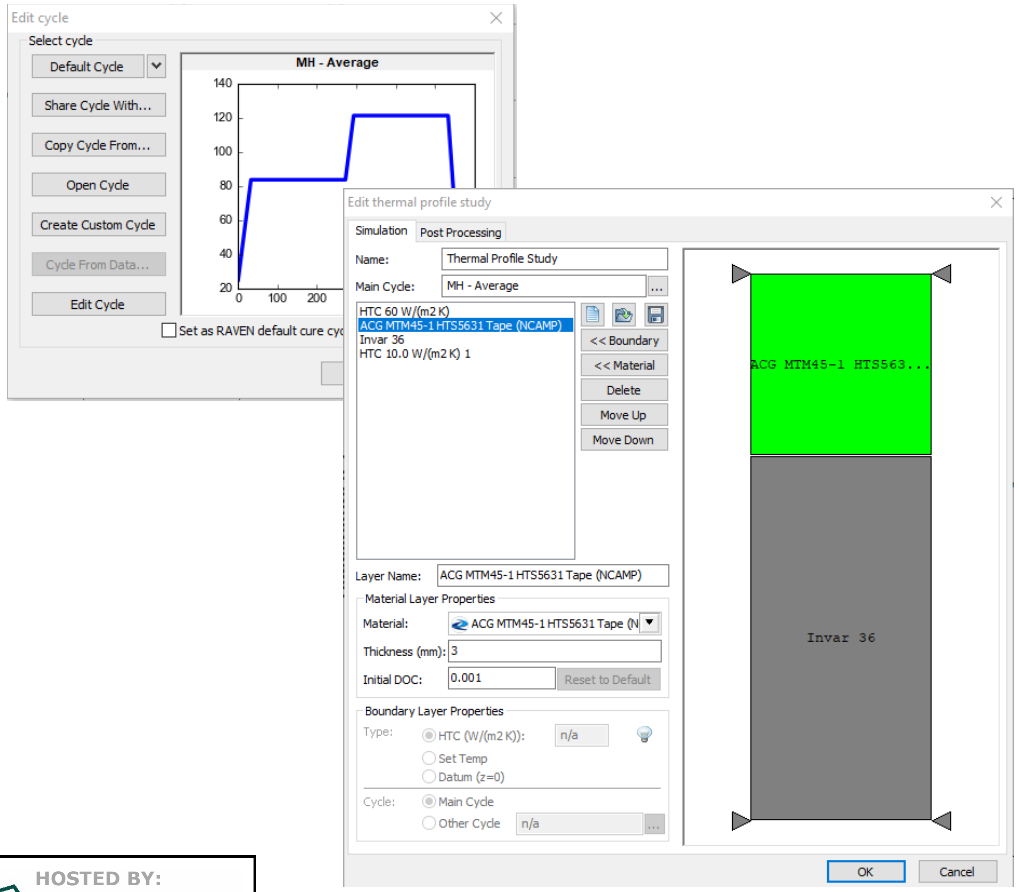
HOT PRESS

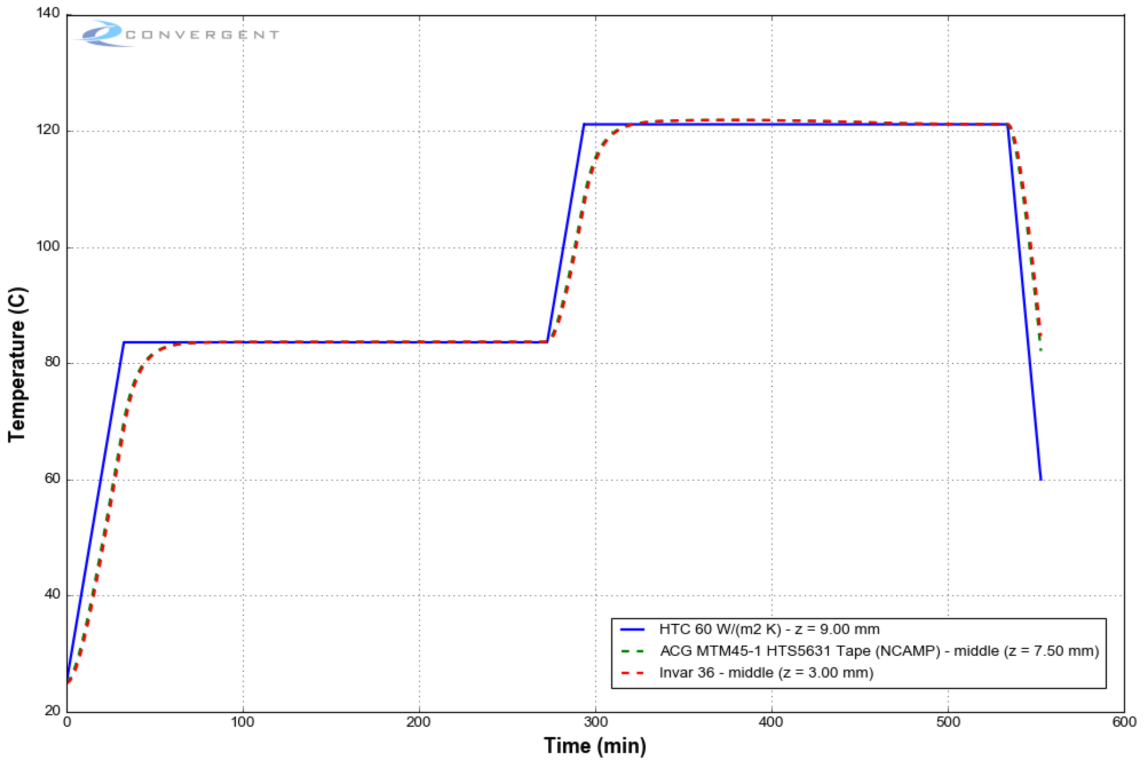
- Typically used with thermoplastic or thermoset prepregs
- Heated matched mould
- Hydraulic or pneumatic press
- Molds are pre-heated electrically or by circulating oil
- Material charge is loaded into the mould cavity and the moulds are closed
- Laminate is held at pressure and temperature for a prescribed amount of time
- Conduction is main heat transfer mechanism



HEAT TRANSFER SIMULATION OF A COMPOSITES PROCESS

- 1D simulation



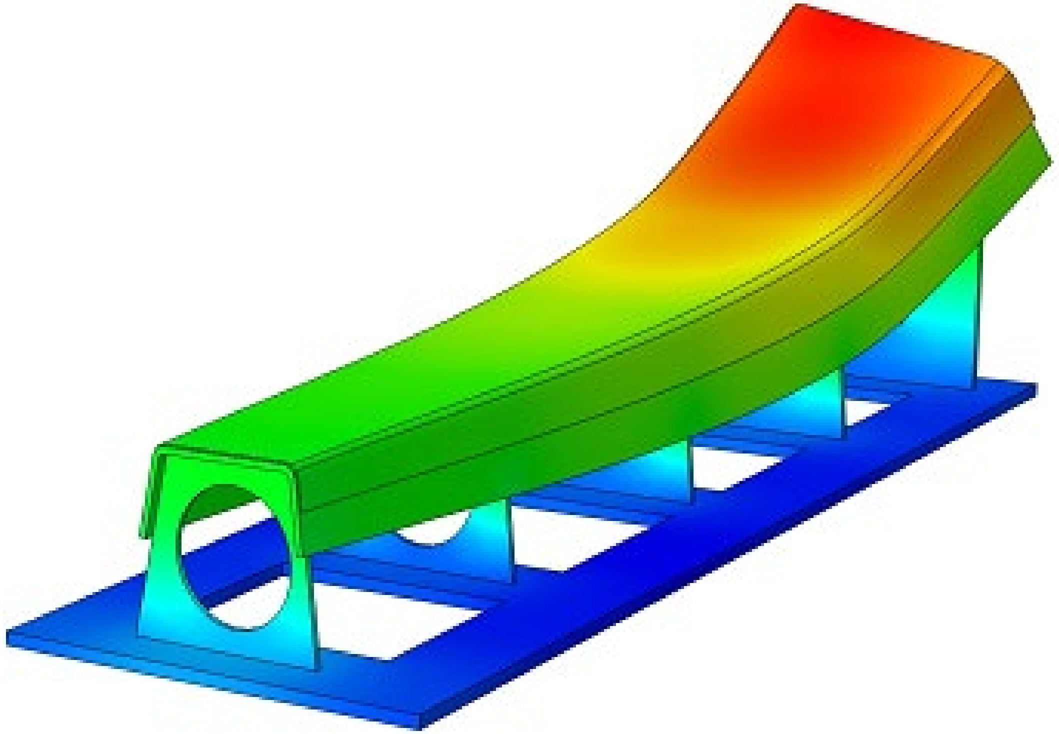


HOSTED BY: CKN Composites Knowledge Network

HOSTED BY: sampe Canada

HEAT TRANSFER SIMULATION OF A COMPOSITES PROCESS

- 3D simulation



Thank you for joining us!

Keep an eye out for announcements on the next AIM events:
Held on the last Wednesday of the month

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Questions?

Today's Webinar will be posted at:
https://compositeskn.org/KPC/A321

HOSTED BY:
CKN
Composites Knowledge Network

HOSTED BY:
sampe
Canada